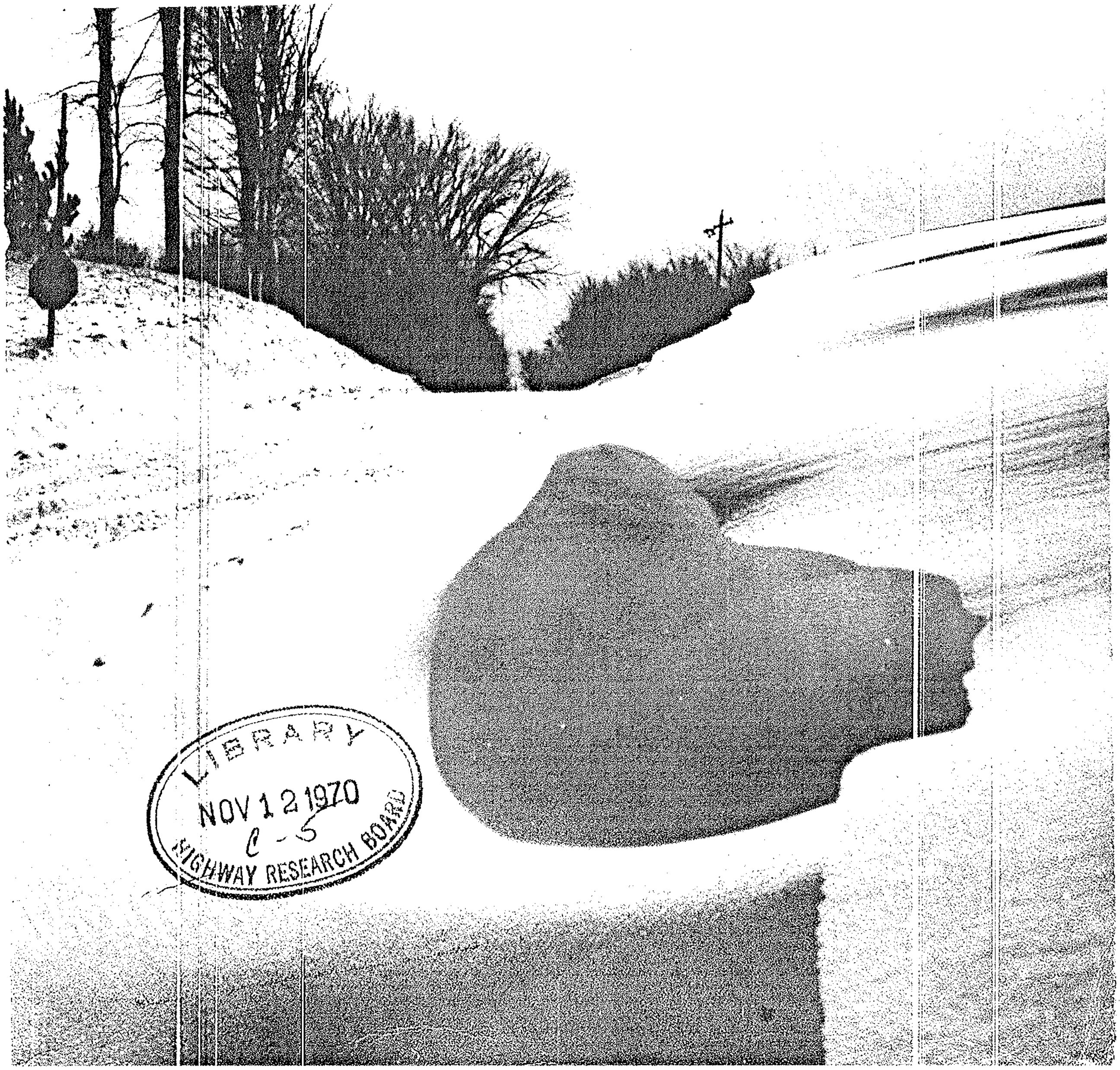
SNOW REMOVAL AND ICE CONTROL RESEARCH

U.S. Army Cold Regions Research and Engineering
Laboratory

Highway Research Board National Research Council
National Academy of Sciences—National Academy of Engineering

Special Report 115



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Special
Report
115

SNOW REMOVAL AND ICE CONTROL RESEARCH

Proceedings of an International Symposium
held April 8-10, 1970

Subject Areas

26	Pavement Performance
40	Maintenance, General
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WASHINGTON, D.C. 1970

INSERT FOR HRB SPECIAL REPORT 115

Because of mail delays, informal discussion comments were not received from authors in Japan until after this report was in press. Several statements submitted by the authors that add clarity to some of their statements during the informal discussions are therefore being included in this insert. They are referenced to the place in the discussion where they apply.

ICE DETECTION, PREDICTION, AND WARNING SYSTEM ON HIGHWAYS, by

Motoya Inoue, Kozaburo Baba, and Yoshiharu Takada

Page 25, response of Inoue to question by Poulin:

There are many factors influencing the surface temperature. Therefore, I am afraid it would be very difficult to predict the surface temperature accurately with only 1 or 2 measurements. The reason why the system is so expensive is not that we had to have many sensors at each sensing station but that we had to have many sensing stations along the route. Accordingly, we had to spend a lot of money on transmission apparatus. I cannot recommend a reduction in the number of sensing stations because the surface temperature varies from location to location depending on many factors such as the physical features of the road, the topography along the road, the local conditions of insolation, and the level of underground water. However, it would be possible to reduce the number of sensing stations if the topography is monotonous and the weather conditions do not vary very much with location.

Page 25, response of Inoue to question by Watkins:

In order to determine the locations, we measured the surface temperatures along the road many times with an infrared thermometer in an experimental vehicle until we got the characteristics of the surface temperature and its fluctuation with locations. The preliminary surveys were conducted during nighttime because we wanted to collect data when the surface temperature was stable. Based on the results of the preliminary survey, we analyzed the distribution pattern of the surface temperature along the route. With the results of the analysis, we calculated the relative coefficients between the surface temperatures from different locations. We then selected the minimum number of sensing station locations that could get information on surface temperatures throughout the route with the confidence of 95 percent. Those analyses were carried out with the aid of computers and were based on data from 51 checkpoints set up every kilometer along the test route of 50 km.

Page 26, response of Inoue to question by Spellman:

The direction and the velocity of the wind have a definite effect on the heat balance of the pavement surface.

Page 26, response of Inoue to first question by Cook:

About 2 m above the road surface. I take into consideration dew point at this height.

Page 26, response of Inoue to second question by Cook:

Yes I do. Dew point is important because of its great influence on the radiation.

SKID RESISTANCE OF SNOW- OR ICE-COVERED ROADS, by

Kaoru Ichihara and Makoto Mizoguchi

Page 114, comment by Ichihara after comment by Balmer:

The measurements of coefficient of friction in this report were made on snowy or icy roads, not on glare ice. Studies of tire friction on ice are conducted by other institutes such as Hokkaido University. When a snow temperature is around the melting point, meltwater remains in the snow layer by an effect of radiant heat, and this meltwater contributes to lower skid resistance. As the temperature drops to well below the freezing point, the surface of snowy or icy roads is considered to be in a dry-ice condition. The skid resistance value then becomes higher than that of a wet-ice condition that is observed around and below the melting pont.

Page 114, response of Ichihara to question by Glauz:

On snowy or icy road surfaces the temperature difference between the road surface and tire tread surface under normal driving conditions would be small. Other research on normal pavements revealed that the effect of tire temperature is relatively small. However, road surface temperature has great effect on skid resistance.

CURRENT RESEARCH ON SNOW REMOVAL AND ICE CONTROL ON ROADS IN JAPAN, by

Raizo Tsuchiya and Motoya Inoue

Page 266, response of Inoue to question by Clary:

The use of infrared lamps is not widespread, but they could be used in limited places such as on bridges and in the vicinity of toll gates and portals of tunnels.

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Foreword

The increased demand for safe and efficient vehicle movement during the winter months has focused attention on the technology and practices for keeping snow and ice removed from roadways and runways. Therefore, the Committee on Snow and Ice Control of the Highway Research Board and the U.S. Army Cold Regions Research and Engineering Laboratory sponsored an international symposium for discussions of the technical aspects of current snow and ice control and of future work in this field.

The Symposium on Snow Removal and Ice Control Research was held at Dartmouth College, Hanover, New Hampshire, from April 8 to 10, 1970. Nearly 150 persons participated either by preparing and presenting papers or by attending the sessions. The subjects of the papers presented ranged from the properties and structural composition of snow and ice through chemical and mechanical technology for use in both forecasting and controlling snow and ice conditions to current practices in the application of this technology.

Informal discussions followed the presentation of each paper, and these were recorded and have been included in this Special Report. Formal discussions were prepared for some of the papers, and these as well as closures by the authors have also been included. In general, the papers are arranged in this Special Report according to the order of presentation during the Symposium.

Contents

A Short History of Man's Attempts to Move Through Snow

L. David Minsk

Man's early need to move in a snow-dominated environment merely required his remaining on the surface. The use of skis undoubtedly began in ancient times, and Stone Age carvings on rocks in northern Norway are the most ancient images of skiers known. Remnants of skis unearthed in Lapland have been dated from 6000 BC by analysis of pollen sticking to them. The early skis were not attachments to shoes or boots, but rather were elongated boots into which the foot was thrust at the rear. Snow did hamper military operations, but provided the surprise for Hannibal in 216 BC to overcome a superior force when he crossed the Alps in early winter contrary to what the enemy thought possible. History is replete with the effects of snow on man's activities and on his battles. Some of the forces to which men were subjected on the North American continent, and their responses to them, form the substance of this brief review of snow removal technology.

In spite of the great influence snow has had through the years on military operations, military requirements historically have not played a significant role in the development of snow removal techniques and equipment. Cities in snow areas had to cope with snow as best they could, using sleighs for transport and later wedge-shaped plows towed behind teams of horses or oxen. The life of cities at times slowed greatly during bad winters. Cotton Mather, the outspoken American clergyman, was moved to deplore the elements that kept his church empty for 2 consecutive Sundays during Boston's snowy winter of 1717. The need to move readily and for any distance was not a great necessity for the mid-nineteenth century city-dweller either. Indeed, the poet of 100 years ago (11) could write:

> O the snow, the beautiful snow,
> Filling the sky and the earth below.
> Over the house-tops, over the street,
> Over the heads of the people you meet,
>   Dancing,
>   Flirting.
>   Skimming along,
> Beautiful snow, it can do nothing wrong.

This sentiment was not voiced by those who built the Central Pacific Railroad from Sacramento east over the Sierra Nevada Mountains in California to meet the Union Pacific at Promontory Point, Utah, in May 1869. During the first winter of construction in 1865-66, thousands of laborers fought to keep the completed portions of the railroad clear of snow by hand shoveling. Many of the locomotives were equipped with pilot plows, wedge-shaped sheet-iron devices attached to the cowcatcher and commonly used on eastern railroads where they proved adequate. They were not adequate to cope with the heavy western snows, however, so a heavy wedge or "bucker" plow was constructed in the Sacramento shops of the Central Pacific in 1866. This first attempt was mounted on 2 ordinary freight car trucks and weighed 12 tons. The wedge flared up at an angle of 45 deg, and then flared outward. In action during its first winter, three 36-ton locomotives pushed the plow into the snow at full speed and kept going until stalled by snow higher than the plow. Men wielding shovels then had to clear the tracks behind the plow before it could be backed out of the cut. Many derailments showed that the plow was too light to hold the rails, so its weight was increased to 19 tons by the addition of pig iron. This heavier plow sometimes required as many as 12 locomotives to drive it through high drifts.

A large crew of men was still carried with the heavy bucker plows to shovel out snowsheds, which had been built in slide areas, and to shovel out the plow itself when it all too frequently got stuck, and sometimes derailed.

The inadequacy of the bucker plow led some to think of better ways of cleaning track. A Toronto dentist, J. W. Elliot, had patented a "Revolving Snow Shovel" in 1869 and built a small hand-operated model, but had never done more to promote his idea. In the same year, and independently, Charles W. Tierney of Altoona, Pennsylvania, received a patent for a mechanical snow removal device consisting of a revolving screw feeding snow into a large rotating fan, the whole mounted on a flatcar and driven by a stationary steam engine. Tierney built a model but was unable to interest any railroad. The first full-scale mechanical plow was the Hawley, exhibited at the Centennial Exposition in Philadelphia in 1876. This consisted of a large vertical screw into which snow was fed through a funnel-shaped casing in front. It proved a total failure when tried by the Canadian Pacific (1).

Others were working on new ideas, however. In 1883 Orange Jull, the mechanically talented owner of a flour mill in the village of Orangeville, Ontario, conceived the idea of mounting a large rotating fan on a railroad car to chop up the snow and cast it aside. Rather than make a model, he interested John S. and Edward Leslie, brothers who operated a machine shop in Orangeville, in building a full-sized operating machine. Jull's original idea was to mount a cutting wheel rotating at high speed in front of a rotating fan wheel; snow would be cut by the knives on the front wheel and fed to the fan, which would cast the snow to the side through an opening in the housing. The Leslie brothers advised Jull to patent his plow, which he did in 1884, assigning the rights to the Leslies who agreed to pay royalties if the "Rotary Steam Snow Shovel" were successful.

The Canadian Pacific became interested in Jull's plow and lent assistance in its construction and subsequent test. The first trials showed that the snow-casting wheel should be reversible so snow could be cast in either direction. This modification was quickly made and appeared satisfactory, so a new plow was built embodying these changes. During the first use in heavy snow in Wyoming during the winter of 1885-86, the machine was unable to overcome the forces developed by the snow moving between the counter-rotating wheels. The Leslies dropped the 2-wheel scheme and adopted a single, reversible fan wheel with reversible cutting knives mounted on trunions on the forward part (Fig. 1). This design proved immensely successful, and orders poured into the Leslies, who by now were having the machines built by the Cooke Locomotive and Machine Works in Paterson, New Jersey. This design has not been radically changed to the present day.

This is not the end of the fascinating story of railroad snow removal and of Orange Jull. Jull and the Leslie brothers disagreed on financial matters and parted company. Because he had assigned the basic patent to the Leslies, he decided to design a completely different device. The resulting "Centrifugal Snow Excavator" was shaped like a huge auger that fed snow to a rotating fan wheel as in his earlier design. Jull formed his own company to manufacture this plow. Altogether he made and sold 10 Excavators. Competitors such as Caldwell's "Cyclone Steam Snow Plow" made claims that had to be disproved in actual track clearing tests, but no plow was as successful as the Leslie machine.

Snow removal practices in cities developed rapidly in the years shortly after the turn of the twentieth century. The key to snow disposal plans in many cities was the use of sewers for flushing away snow hauled or pushed to manholes. Both Pittsburgh and New York City developed these techniques to a high degree, as did a number of smaller cities in the eastern United States, even to the extent of installing water jets in the walls of some manholes to assist in the flushing action. It was found that 2 cu yd/min was the maximum rate snow could be shoveled into a 24-in. manhole without plugging (2). Horse-drawn wedge plows and horse-drawn carts were the extent of the equipment available, and armies of men wielding shovels were the backbone of the snow removal forces. In a February 1914 heavy snowfall in New York City, for instance, over 12,000 men were deployed to man the shovels. Motor trucks for hauling and for pushing small blade plows began to make their appearance around the beginning of the second decade. They lacked traction and power, and not infrequently had to be hauled

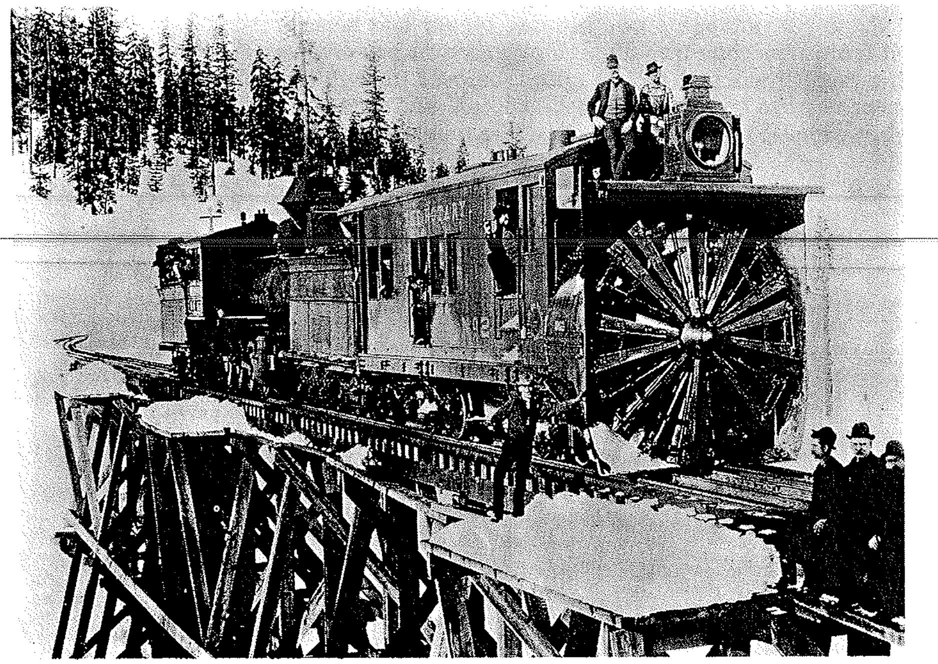

Figure 1. Leslie-type rotary snowplow used in 1890 on lines of the Southern Pacific Company in the Sierra Nevada Mountains. (Photograph courtesy Southern Pacific Company.)

out of drifts by teams of horses. The horse-drawn plow was still the main piece of equipment well into the second decade. In fact, New York City used practically no mechanical equipment until the winter of 1920-21, when 212 5-ton 6-cu yd trucks (White), 100 2-ton 3-cu yd trucks (Mack), 600 tractors, 150 towed blade graders, and 300 blade plows were first used (3).

At a snow removal conference held in 1914 in Philadelphia, one of the earliest on record, one engineer stated that "the same old cart-and-horse methods of snow removal seem to be used that were adopted when the problem became serious some twenty years ago." In his opinion, snow melting devices offered the most likely possibility for improving snow removal practices (4). A lady engineer present (Dr. Marie D. Equi, Portland, Oregon) said she was convinced that engineers were clever enough to invent a device like a steam-heated concrete mixer that would solve the snow removal problem once and for all (5).

It was reported at the Philadelphia snow removal conference that salt was then extensively used for snow removal in Liverpool, London, and Paris. Salt alone was spread on city streets during and immediately after a snowfall, and after the snow had been reduced to a slush by melting and by traffic action, the streets were flushed with water and the slush washed into the sewers. The conference doubted that this practice would ever be successful in the United States because of the heavier snowfalls, and also because the Society for Prevention of Cruelty to Animals raised serious objection to the use of salt. In some cities its use was actually prohibited by ordinance.

The years between 1920 and 1929 marked the most rapid change in snow removal technology on highways. Passage of the Federal-Aid Road Act by the United States Congress in 1916 authorized the federal government to give states financial aid for highway improvement. The piecemeal development of the national highway system was replaced by an integrated road network as a result of legislation passed in 1921 requiring that a federal-aid system be designated and that all federal assistance be concentrated on it. The demand for complete removal of snow from roads grew yearly, and the need for bigger, more capable equipment and better techniques became apparent.

During these years blade plows became bigger and heavier, truck plowing speeds increased from less than 5 to 30 mph or more as power and weight increased, trucks became the most important tool in snow removal (though tractor or horse-drawn wedge plows continued to be made into the 1930's), and rotary plows were developed or adapted for highway use (Figs. 2, 3, and 4). The most common type of rotary plow was the so-

Figure 2. Straight blade snowplows attached to truck in use in 1925 (12).

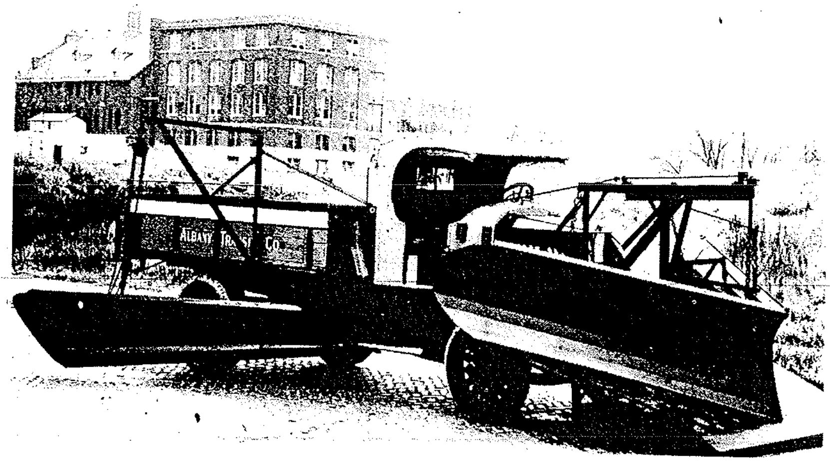

Figure 3. Displacement snowplow mounted on truck used in central and northern New York in 1926 (13).

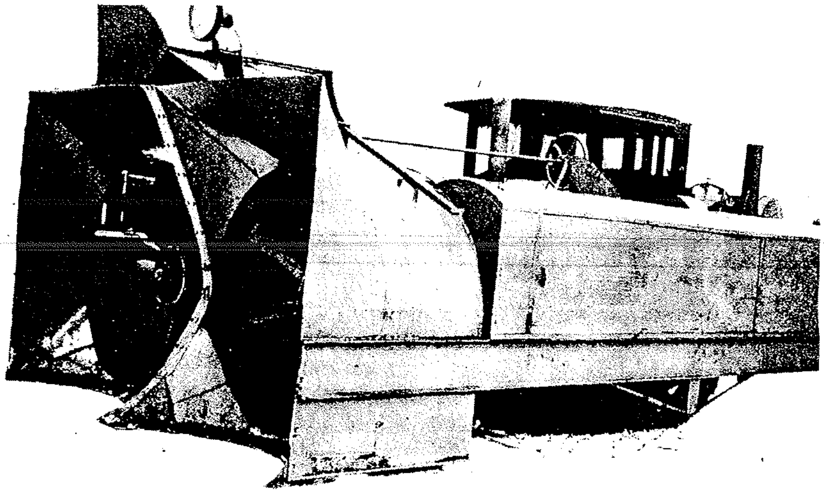

Figure 4. Front-type rotary snowplow mounted on heavy tractor in use in 1926 (13).

called lateral rotary, in which the axis of the rotating elements (usually there were two) was normal to the direction of travel (Fig. 5). The plow, using horizontal augers to feed snow to a centrally located impeller, was developed in the middle of this decade and is one of the few designs of that era to survive to the present day (6, 7, 8).

The first consideration of snow and ice control on highways by the newly organized Highway Research Board occurred at the Second Annual Meeting in November 1922. The Third Annual Meeting Proceedings of November 1923 refer to a proposed study of snow removal to be made by the U.S. Bureau of Public Roads, and also carry the statement that "the committee believes that further research is necessary on this subject, particularly with the end in view of developing snow-removal equipment for highway work" (9).

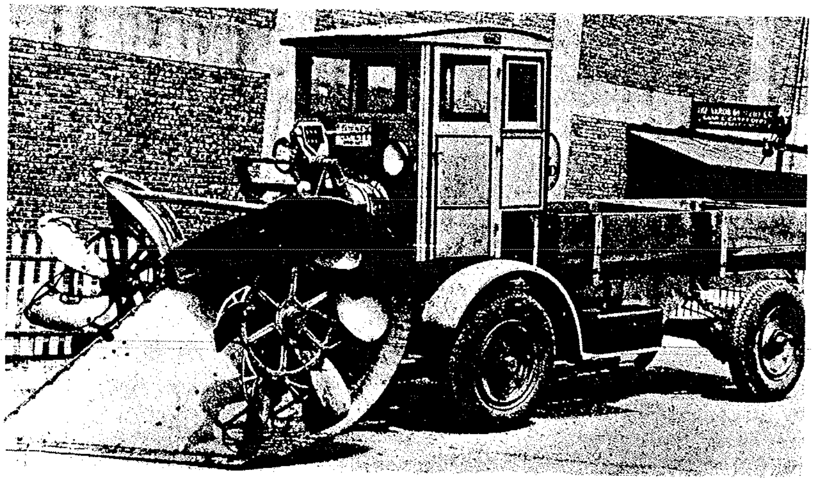

Figure 5. Lateral-type rotary snowplow suitable for mounting on truck used in New York in 1927 (14).

In the Proceedings of the Fourth Annual Meeting of 1924, W. A. Van Duzer of the Pennsylvania State Highway Department had this to say about snow removal equipment:

> It would seem that it is generally agreed that heavy equipment, i.e., caterpillar tractor with V plow, is most practical for moving heavy accumulations of snow, say in excess of 24 inch depth. Lighter equipment, typically 3 to 5 ton motor truck equipped with straight blade of moldboard pattern, is most economical and efficient for moving lighter accumulations of snow.
>
> In estimating the limitations of equipment as above, 24 inches is assumed as the maximum occasional limit for the truck plow; that is, the truck plow is recommended for light work and for occasional drifts up to 24 inches, but the truck and straight blade is not considered adequate for long distances of 24-inch depth.

Even by 1925 highway engineers were debating the value of snow removal from rural highways. Two objections were offered: that the cost of the work exceeded the benefits gained, and that clearing the road of snow increases frost action with intensified heaving resulting in the spring. On the other hand, some advantage to the road structure resulted from snow removal because snow on roads led to cars developing narrow tracks with rutting breaking down the road (8).

Prior to 1941 it was the usual practice to spread chloride-treated sand on compacted snow or ice-covered pavements. Enormous quantities of abrasive materials were required when all roads were sanded rather than only curves, hills, and intersections. Experiments were begun in New Hampshire in February 1941 using sodium chloride alone as an ice preventive. In accord with earlier practice, it was considered desirable to clear the center of a 2-lane road for a width of at least 6 ft. This was accomplished by spreading course-crushed salt at the rate of ¼ lb/sq yd for a width of about 2 ft along the centerline immediately after completion of snowplowing. The equipment used in this early work was open-bed stake or dump trucks hauling bagged chemical, requiring a workman to load the funnel of a gravity-feed salt distributor. Though the comparison is subject to some simplifications, the cost of snow removal and ice prevention in the winter of 1944-45 in which nearly all straight salt was used for ice control was about $260 per mile, compared with $312 per mile in the winter of 1940-41, the last winter in which abrasives were used exclusively. Moreover, the average snowfall was 18 in. greater in 1944-45 than in 1940-41 (10).

I have dwelt at length on railway and city snow clearance because of its importance in the historical development of snow control technology. This review is necessarily spotty, and I must leave to others more detail of the important work that has been carried out in the United Kingdom, Europe, Scandinavia, Japan, and Russia.

But from this overview I think you can see that the technology of snow control today is not much different from that of earlier days I have described. In a sense we are still in the "cart-and-horse" days decried at the 1914 Philadelphia conference. Let us not substitute quantity for innovative ideas. It is the purpose of this Symposium to describe today's new approaches, and to stimulate tomorrow's.

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Classification of Snow and Ice on Roads

Seiiti Kinosita and Eizi Akitaya

Snow on roads appears in many different types and changes ceaselessly by the action of traffic, snow removal work, and weather. Attention must be given to these changes in the study of snow removal and ice control operations and winter driving. Measurements were taken of density, hardness, temperature, and soil content; and micrographical observations were made in the winters of 1968-1969 and 1969-1970 on thin snow layers covering urban arterial roads in Hokkaido, Japan. Based on these data, the following classifications are proposed: new snow, composed of snowflakes; powder snow, composed of loose grains 0.05 to 0.3 mm in diameter and blown up by a passing car; granular snow, composed of loose grains 0.3 mm or larger in diameter, never blown up, and formed by thermal metamorphosis, mechanical mixing, or chemical treatment; packed snow, composed of a network texture of grains of 0.05 to 0.3 mm in diameter; ice crust, formed by freezing of wet packed snow; ice film, formed by freezing of meltwater film; and slush, formed by melting of snow and splashed by a passing car.

Snow layers on roads carrying traffic are usually thin; the thickness is ordinarily less than several centimeters. The snow changes ceaselessly by the action of traffic, snow removal work, and weather. It is important to understand the characteristics of the different types of snow that these changes produce.

Snow and ice were observed on urban arterial roads in Hokkaido, Japan, in the winters of 1968-1969 and 1969-1970. Measurements were taken of density, hardness, temperature, free water content, and soil content; micrographical observations were made of the textures. Based on these results, 7 types of snow and ice on roads are proposed: new snow, powder snow, granular snow, packed snow, ice crust, ice film, and slush.

Sometimes one type will exist in a single layer on roads, and at other times a combination of types will exist in layers. Changes from one type to another occur frequently and are caused by mechanical mixing, chemical treatment, or heat absorption. The heat is supplied from warm air, solar radiation, or car tires rotating at high speeds. Measurements were made of the tire temperatures.

OBSERVATION METHODS

Snow layers covering roads were cut vertically from the snow surface to the pavement; a cross section is shown in Figure 1. Measurements were taken of the following:

1. Density (ρ, g/cm^3)—If the snow was composed of loose grains, they were scraped together gently and placed in a box of 100 cm^3. The box was then weighed. If snow was compact, a lump was cut out of the layer with a small hatchet. The sides of the lump were shaved off with a carpenter's saw or plane to make it a rectangular cube, and then its dimension and weight were measured.
2. Hardness (H, kg/cm^2)—Kinosita's hardness gage (1) was used. The measured value H represents the resistance suffered by a body when it is dropped. The height of the fall and the depth of the hollow made on the snow surface were measured.
3. Temperature (T, deg C)—A thermistor was used.

4. Free Water Content (W_W, percent)—$W_W = a/\rho \times 100$, where a is the weight of free water contained in 1 cm^3 of snow. Yosida's combination calorimeter (2), which is composed of 2 containers (snow container and hot water container), was used.

5. Soil Content (W_S, percent)—$W_S = b/\rho \times 100$, where b is the weight of soil contained in 1 cm^3 of snow. The weight of a snow sample was measured before and after drying.

Micrographical observations were made in the cold room after snow samples had been brought in from observation points. Close-up photographs of grains of the snow and microphotographs of a thin section of the snow were taken. The thin section with a thickness of about 0.1 mm had been prepared by the aniline method (3).

The temperature of the tire of a running car was measured with an infrared radiation thermometer. A circular opening 10 cm in diameter was made in the center of the cover about the tire of a rear wheel of a Jeep (Mitsubishi J-30). The sensing head of this thermometer was directed to the top of the moving tire through the opening, and the measurement was made inside the moving car.

Questionnaires requesting information concerning weather conditions, snow removal work, snow features, and several other relevant quantities obtainable by simple measurement were sent beforehand to a number of snow removal departments (4). The questionnaires were filled in at designated observation points 3 times a day (early morning, daytime, and evening) for the duration of several days.

OBSERVATION POINTS

Observations were made at several points on the national highway near Sapporo City, where traffic has a density of 500 to 6,000 vehicles per day. One of the points was on a test road designed to investigate snow-melting effects by chemicals, where 50 to 80 g/cm^2 of calcium chlorides in pellet form were spread on the snow surface every snowy day after the snowplow had passed or when it started snowing. The following are the location of observation points: Route 5, Otaru, Kutchan, Inahotōge; Route 230, Ishiyama, Misumai, Nishikibashi (site of test road), Usubetsu, Nakayamatōge; and Route 231, Ishikari.

CROSS SECTION OF THE SNOW LAYER ON ROADS

A cross section of the snow on roads obtained at Usubetsu along Route 230 on January 28, 1969, is shown in the upper part of Figure 1. The snow is composed of 3 layers: powder snow, packed snow, and ice (each characteristic will be described later). The powder snow lies on top and is no more than 0.1 to 0.2 cm thick. The numbers on the first line below the cross section in Figure 1 indicate the thickness of total snow layers. The thickness is less than 4 cm at the portion of the road traveled by vehicles. The numbers within the parentheses indicate the thickness of ice adhering to the pavement. The numbers on the second and third lines indicate the density and the hardness of the packed snow respectively. They are larger than those of naturally

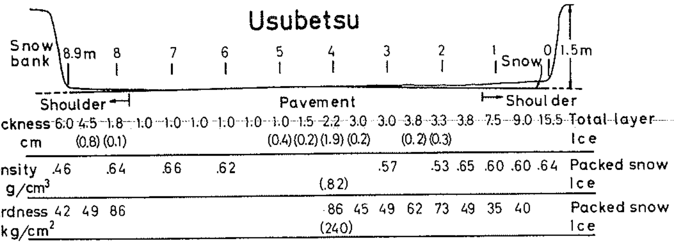

Figure 1. Cross section of snow obtained on Route 230 at Usubetsu on January 28, 1969, and composed of powder snow, packed snow, and ice. Air temperature was -4 C and snow temperature was -3 C.

TABLE 1

CLASSIFICATION OF SNOW AND ICE ON ROADS

Classification	Characteristics	Composition	Density (g/cm^3)	Hardness (kg/cm^2)
New snow	Exists immediately after a snowfall	Snowflakes (Fig. 6)	0.1	
Powder snow	Blown up by a passing car and drifts along the pavement surface (Fig. 2)	Loose grains 0.05 to 0.3 mm in diameter (Fig. 7)	0.27 to 0.41	
Granular snow	Never blown up and formed by thermal metamorphosis, mechanical mixing, and chemical treatment	Loose grains 0.3 mm or larger in diameter (Figs. 8 and 9)	0.28 to 0.50	
Packed snow	Formed by compaction of powder snow (Fig. 3)	Network texture of grains 0.05 to 0.3 mm in diameter (Fig. 10)	0.45 to 0.75	20 to 170
Ice crust	Formed by freezing of wet packed snow and more than 1 mm thick	Polycrystalline ice with air bubbles 0.1 to 0.5 mm in diameter (Fig. 13)	Over 0.75	90 to 300
Ice film	Formed by freezing of melt-water film and less than 1 mm thick	Polycrystalline ice with tiny air bubbles 0.01 to 0.1 mm in diameter (Figs. 11 and 12)		
Slush	Formed by melting of snow and splashed by a passing car (Fig. 5)	Loose grains 1 mm or larger in diameter (Fig. 14)	0.8 to 0.95	

deposited snow. The surface was hard enough to support vehicles and was a little slippery. The numbers within the parentheses on the second and third lines indicate the density and the hardness of the ice.

Several lumps were taken from the layers and carried to the cold room where they were observed micrographically and their soil contents and specific resistances of meltwater were measured. Soil contents of 2 packed snow samples were 0.07 and 0.15 percent. Specific resistance of one meltwater sample was 1.7 × $10^4\ \Omega$ cm.

Similar observations were made at other observation points.

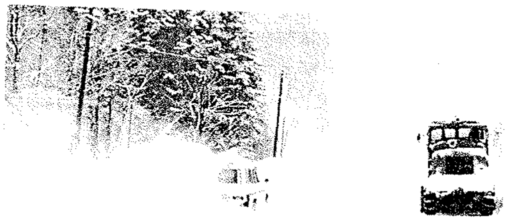

Figure 2. Powder snow, blown up by a passing car.

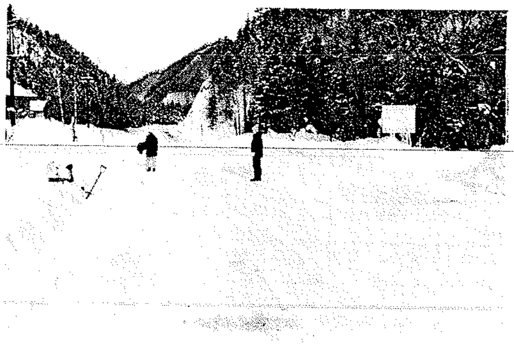

Figure 3. Packed snow.

CLASSIFICATION

Based on the results of the observations obtained in the winters of 1968-1969 and 1969-1970, 7 types of snow and ice on roads are proposed. These are given in Table 1.

These types of snow and ice appear sometimes as a single layer and at other times as a combination of 2 or more layers, as shown in Figures 1 and 4. The following combinations have been observed (listed in order from top to bottom layer): (a) new snow, powder snow, granular snow, packed snow, and ice crust or ice film (more than 2 among these 5 types are stratified with upper ones always above lower ones); (b) ice film and packed snow; and (c) slush and ice crust or ice film.

CHANGE OF ONE TYPE INTO ANOTHER

New Snow to Powder Snow

When cars run over new snow, it changes into powder snow. Snow grains

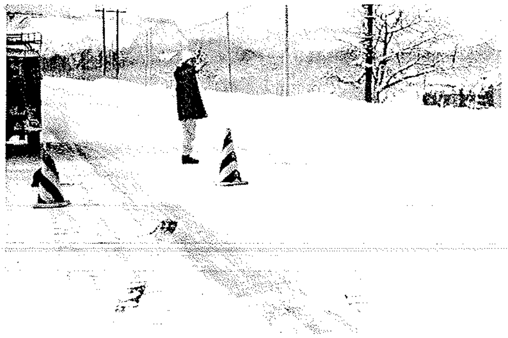

Figure 4. Two stratified layers of powder snow and ice film. Ice film became visible by the trace of sliding tires.

Figure 5. Slush, splashed by a passing car.

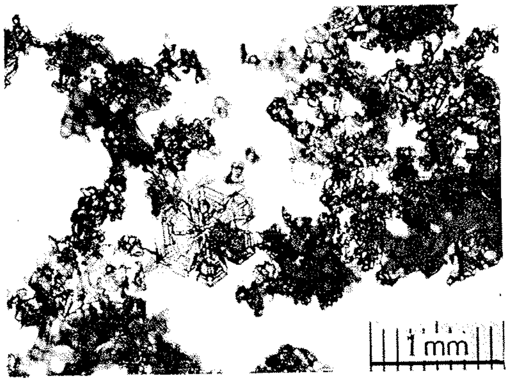

Figure 6. New snow (density 0.10 g/cm^3).

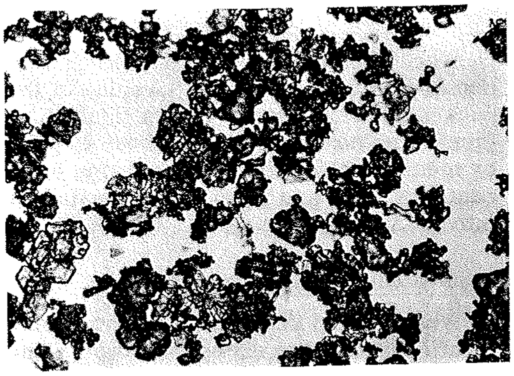

Figure 7. Powder snow (density 0.27 g/cm^3).

composing both types of snow are almost of the same dimension. However, some grains of the powder snow have a more rounded form, as shown in Figure 7, whereas snow flakes of the new snow are angular, as shown in Figure 6. The metamorphism is due to thermal effects; the heat from the tires of running cars is believed to account for it. The temperature of the tires is dependent on the air temperature, the running speed of the car, the character of the snow, the driving hours of the car, and weather conditions. When the car runs at a high speed, the temperature of the tires rises very often above 0 C, as given in Table 2.

TABLE 2

TEMPERATURE OF REAR WHEEL TIRES

Snow Type in Top Layer on Roads	Air Temperature (deg C)	Car Speed (km/hour)	Tire Temperature (deg C)
Powder snow	-10	60	0 to 2
		40	-4 to 0
	-4	40	2 to 3
Packed snow	-13	60	14
		50	10
		40	6
	-8	50	10 to 15
		40	9
Ice film	-1	40	7 to 13

Note: Measured in the running car after a driving time of more than 20 minutes.

Powder Snow to Granular Snow

When powder snow exists on an ice crust, an ice film, or the pavement during heavy traffic, the snow grains come closer and form larger grains but do not physically connect with one another. The cohesive force among small grains is due to the surface tension of meltwater films covering them, and the melt is caused by the heat from the tires. When the diameters of the grains exceed about 0.3 mm, the grains are never blown up by a passing car. Cohesive force decreases with the increasing of the diameter of the grains. If the diameter exceeds a critical value (about 1 mm), no more cohesion occurs. A photograph of granular snow is shown in Figure 8.

On the area where chemicals are applied to accelerate melting, powder snow changes into granular snow by the same mechanism except that the liquid film covering grains is formed owing to the lowering of the melting point. Traffic assists in mixing the chemical with the snow grains. Granular snow produced in this way is shown in the photograph in Figure 9. One grain is an assemblage of many tiny grains that have the same dimension as those of powder snow.

Powder Snow to Packed Snow

When powder snow is compacted by mechanical mixing such as the action of traffic or the snow removal work of a plow or grader, it changes into packed snow. Ice bonds are formed through sintering between snow grains in contact with each other (5). A network connection is thus produced, but it leaves the dimension of each snow grain unchanged, as shown in Figure 10.

Packed Snow to Granular Snow

When chemicals are scattered on the surface of packed snow, a part of the snow becomes liquid owing to the lowering of the melting point. The network connections in the packed snow are covered by a liquid film when packed snow melts to the extent that its free water content reaches about 20 percent. It becomes easy for bonds to be broken by mechanical action so that grains become separated to form loose grains. They then come together and form larger grains by the same mechanism that changes powder snow into granular snow.

Packed Snow to Ice Crust

When packed snow melts to the extent that its free water content exceeds the maximum capacity, the excess meltwater spreads downward and fills the air space in the snow mass contiguous to the pavement or the ice crust below (Fig. 13). If the water freezes again in cold weather, the snow changes into ice crust. The ice crust becomes thick by repetitive melting and freezing processes.

Formation of Ice Film

Ice films are formed by the freezing of meltwater film. The meltwater film appears very often on the pavement and sometimes on the top of the packed snow. The

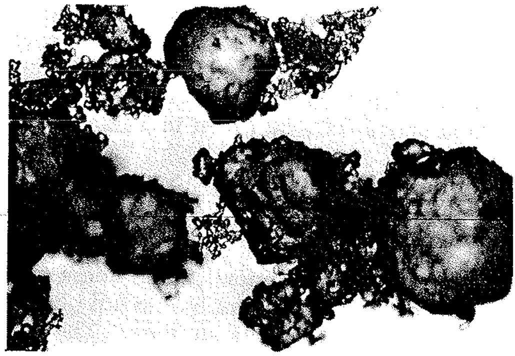

Figure 8. Granular snow (density 0.46 g/cm^3) formed by mechanical mixing.

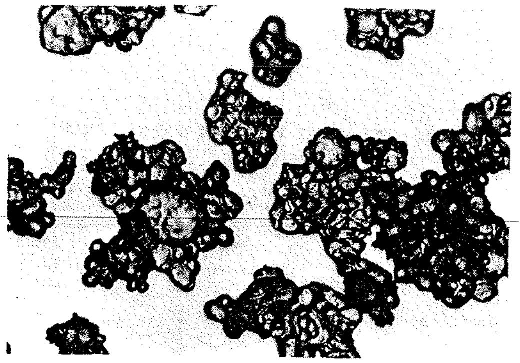

Figure 9. Granular snow (density 0.41 g/cm^3) formed by chemical treatment.

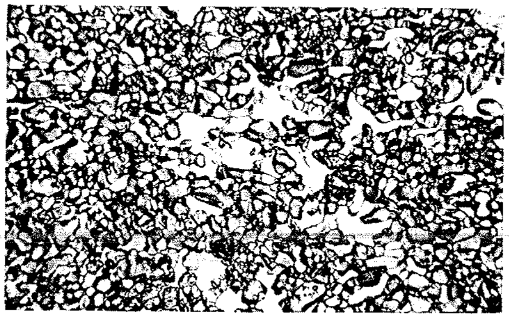

Figure 10. Packed snow (density 0.60 g/cm³), thin section.

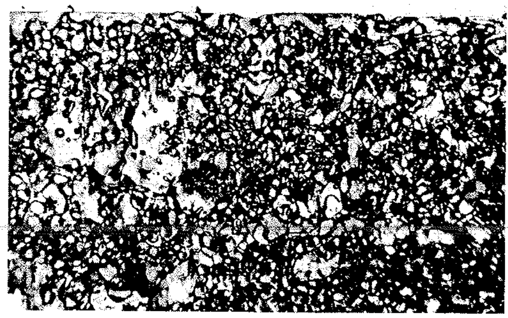

Figure 11. Vertical section of packed snow showing the presence of ice film at the top, thin section.

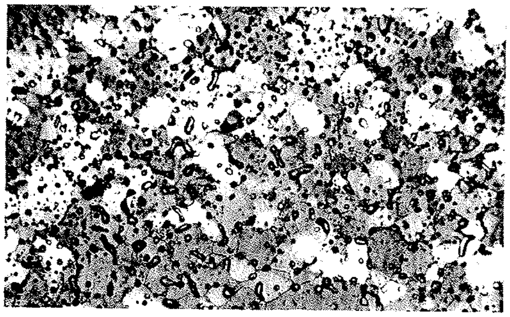

Figure 12. Surface view of ice film covering packed snow taken by polarized light, thin section.

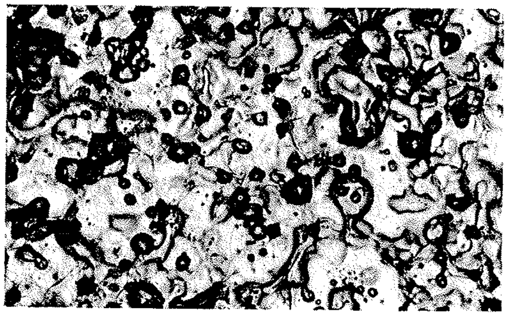

Figure 13. Ice crust (density 0.85 g/cm³), thin section.

Figure 14. Slush (density 0.92 g/cm³, dry density 0.60 g/cm³).

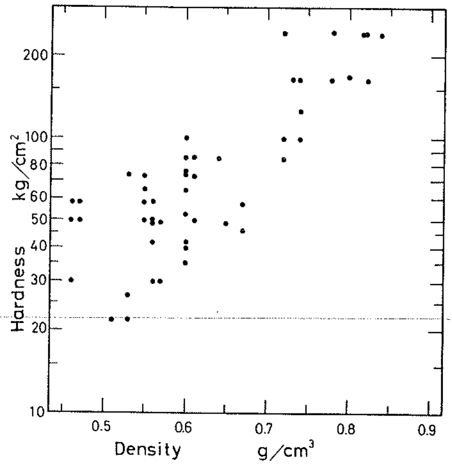

Figure 15. Relationship between hardness and density of dry packed snow.

presence of the former and the microtexture of the latter are shown in Figure 4 and Figures 11 and 12 respectively. Each type of snow and ice can form by the heat supplied from warm air, solar radiation, and tires.

Formation of Slush

When snow melts into water, the mixture of snow and water is splashed by a passing car, as shown in Figure 5. This type of snow, called slush, is composed of loose grains larger than 1 mm in diameter, as shown in Figure 14. According to the observations, the density ranged from 0.8 to 0.95 g/cm^3, the dry density from 0.45 to 0.6 g/cm^3, and the free water content from 30 to 50 percent.

RELATION BETWEEN HARDNESS AND DENSITY OF PACKED SNOW

In the suburbs, packed snow is predominant on roads (Fig. 3). Both the hardness and the density range widely as shown by the data in Figure 15. The relation between them is approximately given by

$$H = c\rho^4$$

where c, the constant obtained from the relation, ranges from 400 to 600. For naturally deposited snow, the value of c is approximately 100 in this relationship, ρ ranges from 0.1 to 0.4 g/cm^3, and the temperature is below 0 C (1).

TRAFFIC PROBLEMS DUE TO SNOW

The important traffic problems due to snow on roads are the decrease of visibility, the difficulty of snow removal work, and the slippery condition of the road surface. Powder snow remains in the air for a long time after a car has passed by and blown it up, making visibility poor (Fig. 2). Drivers of following cars have trouble seeing the direction of the road. Efficiency of snow-removal work changes with the hardness and the density of snow and ice, in particular for packed snow and ice crust. Ice film makes the road surface very slippery, as the traces of sliding tires in Figure 4 show. The relationships of these problems to snow and ice on roads will be the subject of future research.

ACKNOWLEDGMENTS

Planned by the Committee on Research of Snow on Roads, Japan Construction Mechanization Association, under the chairmanship of Dr. Ishihara, this study has been discussed among the committee members. The authors express their thanks to them. Many members on the staff of the Institute of Low Temperature Science, Hokkaido University, cooperated in carrying out the field research. The authors are greatly indebted to them. Special thanks are expressed to Professor Z. Yosida for his valuable comments.

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Informal Discussion

M. E. Volz

Is this the temperature of the driving tires that you are measuring? Is there a differential between it and the tire that is rotating freely? Is there a direct relationship between speed, weight, tire pressure, and so on, and is it a direct ratio, something that you can compute or something that you got by observation and for which you have no formula? I am interested from the airplane pilot's viewpoint rather than from the viewpoint of a driver of a highway vehicle. Can we determine what the temperature will be in an airplane tire, for example, that is being driven over this ice-rubber interface, if you would like to call it that? Can you compute what the tire temperature will be, or was this just an observed temperature?

Kinosita

We measured the driving tire's temperature. We believe that there is a direct relationship between the speed, weight, tire pressure, and snow type and the driving tire's temperature; but we have not yet found any formula for it. We have never measured the temperature of a driving airplane tire on a snow surface, but you may use an infrared radiation thermometer to determine it.

Ambrose Poulin

What accuracy do you think you have in the measurement of tire temperature? Is it within ±5 deg?

Kinosita

It is within ±1 C.

Poulin

Do you have auxiliary measurements by other methods to determine the accuracy of your radiometric temperatures?

Kinosita

We measured the tire's temperature just after stopping the car with an infrared radiation thermometer and a thermistor. Both measurements gave the same value with the accuracy of ±1 C. We determined the accuracy of our radiometric temperature by measuring the surface temperature of the mixture of ice and water, which is just 0 C.

Volz

I have observed that when a pilot taxis an airplane or drives a car through new snow, mechanical work is done on the snow by the vehicle. It takes additional power to move the vehicle through the snow. Comparatively speaking, is the increase in tire temperature more important than the mechanical work that the vehicle does on the snow as far as melting is concerned?

Kinosita

Mechanical mixing is more important.

Volz

Does the mechanical mixing process increase the temperature?

Kinosita

Yes.

Peter Schaerer

Have you any practical experience with the suggested snow classification system? In order to determine the various classes of snow, it appears to be necessary to make an observation of the crystal shape. Can the man on the road, e.g., the maintenance foreman, do this, or can only an expert scientist classify the snow?

Kinosita

Our classification system is just a suggestion for further use. The observation of the crystal shape may be helpful, but it is not necessary for practical use.

A. G. Clary

Have your operating people made use of this system?

Kinosita

Yes.

Schaerer

Has this worked out?

Kinosita

Yes.

Clary

Has it worked out very well? Did they understand the procedure very well?

Kinosita

The maintenance foremen to whom we explained the procedure understood it very well.

Ice Detection, Prediction, and Warning System on Highways

Motoya Inoue, Kozaburo Baba, and Yoshiharu Takada

A system has been developed by which antifreezing action can be taken, e.g., spreading chemicals, and warnings can be provided to drivers to force slow driving. The system consists of the following 5 parts: (a) meteorological observation devices installed on roadway or roadside for measuring air, pavement, and underground temperature, wind direction, wind velocity, radiation, and humidity; (b) road surface moisture meter installed on roadside for measuring scattering of light and electric conductivity; (c) data processing equipment installed in the control center for use in predicting temperature transition and discriminating road surface moisture state; (d) data transmitter consisting of A-D converters and wireless or wire transmitters for transmitting data between observation sites and control center and between control center and warning signs; and (e) warning sign that has a changeable message and provides drivers with information on slippery conditions. With the use of this system we failed only once in 43 times (a skill score of 0.86) to predict at 5:00 p.m. that ice would form the following morning; we had a skill score of 0.96 in predicting 2 hours beforehand that ice would be forming.

Meteorological phenomena such as rain, snow, ice, fog, and wind occurring on highways present obstacles for road maintenance and driving. In particular, ice film forming on road surfaces, snowfall, and snow coverage are directly connected with possible traffic accidents, so that countermeasures against these obstructions are of particular importance. An information system has been developed to detect, predict, and give warning of road icing.

Prior to the development of this system, extensive survey and study were carried out. These included a meteorological survey of highways throughout Japan; a survey of traffic and snow removal and ice control; a theoretical analysis of predicting meteorological phenomena on highways; the development of meteorological instruments, system design, and operation of meteorological information; and similar considerations.

COMPOSITION OF ROAD ICING INFORMATION SYSTEM

The information system connected with slippery roads consists of the following 5 units: meteorological observation instruments, road surface moisture meter, data processing equipment (data controller), data transmitter, and electric warning signs. A diagram of the system is shown in Figure 1.

Meteorological Observation Devices

These instruments (Fig. 2) are used to observe meteorological elements that have a potential effect on roads and the detection and prediction of road icing. These elements include: pavement temperature (-0.5 cm), underground temperature (-5, -10, -20, and -50 cm), air temperature (+150 cm), dew point temperature (+150 cm), net radiation (+200 cm), wind direction (+200 cm), wind velocity (+200 cm), and road surface moisture.

These observations are recorded and converted into electric signals that serve as input signals for the data processing equipment.

Road Surface Moisture Meter

This device (Fig. 3) uses 3 kinds of observations as input: electrical conductivity, the scattering of light, and the temperature of road surfaces. It compares the input

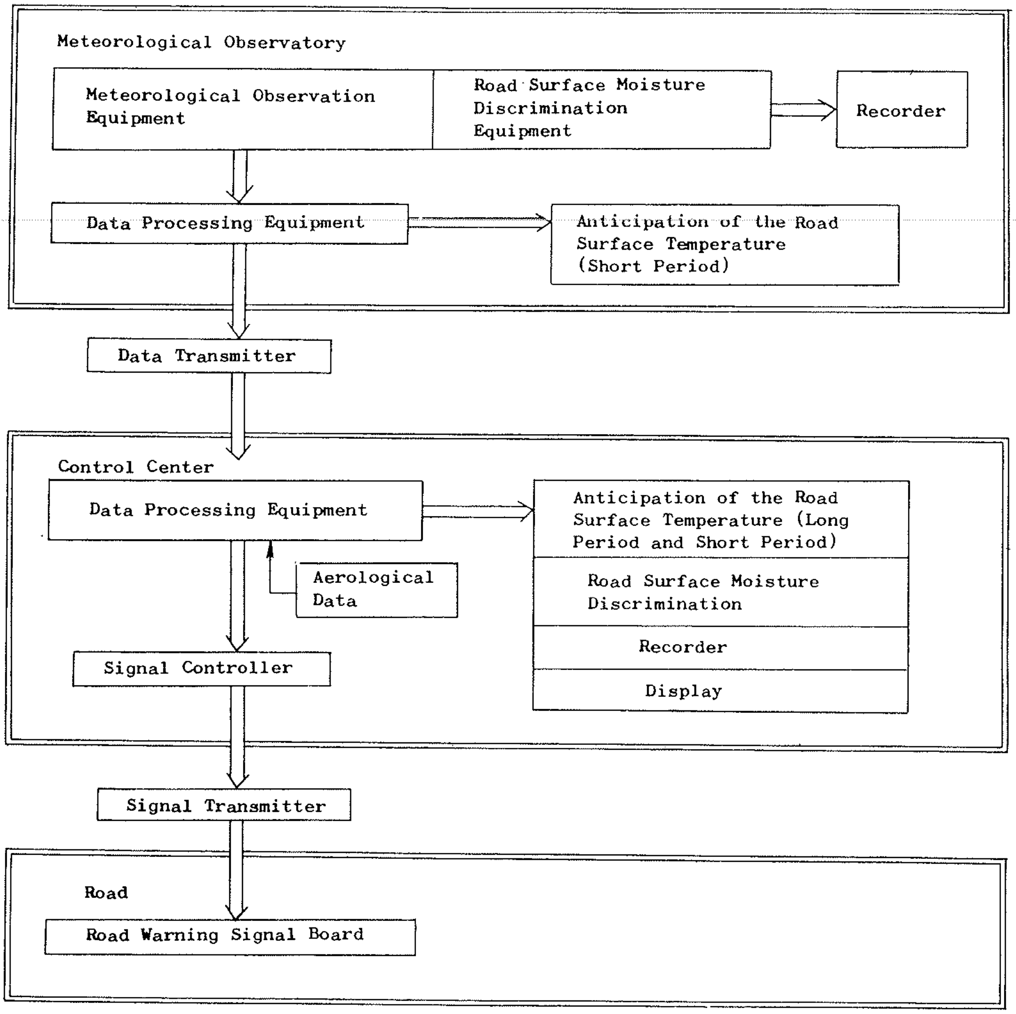

Figure 1. Diagram of the ice detection, prediction, and warning system.

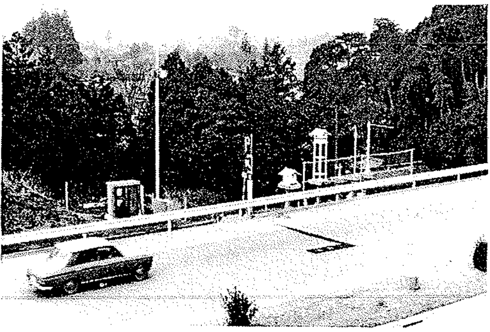

Figure 2. Meteorological observation devices.

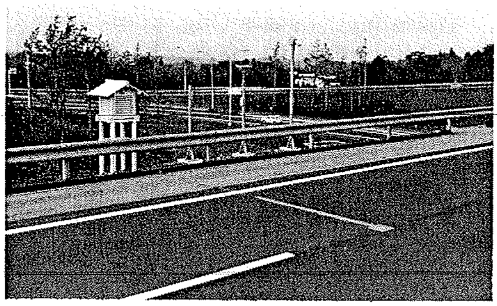

Figure 3. Road surface moisture meter.

with standard values that have been preset empirically and indicates 4 kinds of road conditions by discriminating through a matrix circuit.

1. Dry—There is no danger of icing because there is little moisture on the road surface.
2. Wet—Some moisture is on the road surface, but it is not freezing. The road temperature is above 1.5 C.
3. Prestage of freezing—The road is slushy with snow and water or some moisture is present at a surface temperature of 0 to 1.5 C. This also includes the situation where icing is prevented even at subzero temperatures by spreading a high density chloride.
4. Ice—There is a danger of icing, or the road is already icy with moisture at subzero temperatures.

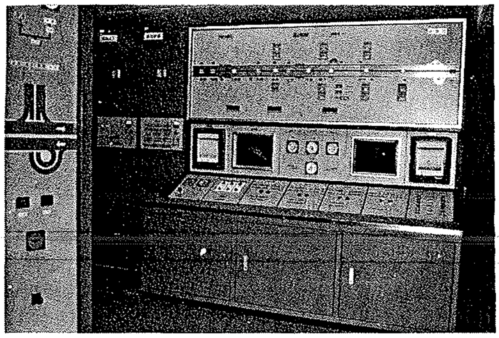
Figure 4. Data processing equipment installed in control center.

Data Processing Equipment

This equipment, installed at the control center (Fig. 4), indicates and processes data obtained at each observatory, and also predicts pavement temperatures with a built-in pavement temperature prediction device.

The prediction is made in 2 ways depending on the time involved. A long-range forecast of pavement temperatures covers up to 15 hours from 5:00 p.m. to 8:00 a.m. the following day; a short-range forecast predicts temperatures continuously 2 to 4 hours in advance of a given time between the hours of 5:00 p.m. and 8:00 a.m.

A prediction formula is previously prepared by analysis of meteorological data obtained at the observatories, and the prediction simulator provides a short forecast of pavement temperatures. In the case of long-range predictions, some types of upper air information are added to the meteorological data fed on-line from each ground observatory. A discriminant method is used here to distinguish whether pavement temperatures are above or below freezing. Whenever pavement temperatures are forecast to fall to freezing degrees, in both methods of prediction, a warning sign appears on the control panel.

Data Transmitter

The device transmits signals from meteorological observatories to the data processing system at the control center or from the control center to the warning signs along the roadside. Observations are wire-transmitted as analog signals when short distances are involved and as digital signals converted by an A-D converter when long distances are involved.

Electric Warning Sign

When moisture appears, such as snow coverage of the road surface, a warning sign is indicated on the roadside sign boards according to the ice prediction. Sign messages, formed by electric variable letters, may be slow-down, ice, fog, snow, gales, and the like. Selection and flashing of the electric letters are controlled from the operation board located at the control center. Automatic control of these signs is also possible. A warning sign is shown in Figure 5.

STUDY OF PREDICTION METHOD OF PAVEMENT TEMPERATURES AND RESULTS

Ice film on road surfaces is formed when pavement temperatures fall to freezing in the presence of moisture on the road surface. Because moisture on a road surface is a result of extremely complicated phenomena, prediction of pavement temperatures is much more difficult than an ordinary weather forecast. The observation stage, therefore, was previously confined to detection.

Detailed surveys and studies have been carried out on icing phenomena on road surfaces throughout Japan. In addition, a study on methods of predicting pavement temperatures was also conducted using analytical methods of heat balance, thermal conductivity, pattern, and statistics on the basis of road and air meteorological data of the particular district.

Figure 5. Warning sign.

Pavement Temperature Forecast Through Heat Balance and Heat Conductivity Analyses

The heat balance on a road surface is not only a basis for clarifying the phenomena of road icing but also a prerequisite for controlling road snow and ice by road heating, using sprinklers, and spreading chemicals (chlorides). An equation of the heat balance is expressed as a summation of a certain amount of time in regard to the total heat flux between unit area of the road surface and space.

$$R = LE + P + A + X$$

where, in this case,

R = net radiation ly/min,
LE = heat loss by evaporation,
P = heat flux caused by advection between the road surface and air,
A = heat flux between the road surface and underground, and
X = direct contact heat transfer caused by rain showers and such.

The heat sum of the empirical formula is calculated according to each term. The heat flow several hours in advance can be estimated from the heat flow at the time of observation, thus enabling a forecast of road surface temperatures to be given by the simulator.

Prediction Through Pattern Analysis of Pavement Temperatures

This prediction method enlists the aid of harmonic analysis using a diurnal fluctuation of road surface temperatures according to the weather as a periodic curve.

$$Y = a_0 + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx)$$

TABLE 1

HARMONIC ANALYSIS OF DIURNAL FLUCTUATION OF ROAD TEMPERATURES

Type of Day	a_0	a_1	a_2	a_3	b_1	b_2	A_1	A_2	a_1/b_1	φ_1 (deg, min)	a_2/b_2	φ_2 (deg, min)
Clear	4.07	9.52	4.32	1.32	5.57	2.19	11.03	4.85	1.71	59 40	1.97	63 06
Fine	5.80	7.64	4.42	1.66	5.05	2.01	9.16	4.85	1.51	56 31	2.20	65 31
Cloudy	7.62	5.32	3.01	0.85	4.54	1.55	6.99	3.38	1.17	49 33	1.95	62 48
Rain	13.52	4.46	1.88	0.24	2.53	0.92	5.12	2.09	1.77	60 28	2.04	63 56
Snow	5.81	3.58	1.57	0.85	2.09	0.26	4.14	1.59	1.71	59 43	5.98	80 31

TABLE 2

ALLOCATION OF VARIATES

No. of Data	Symbol	Kinds of Data		No. of Regression Elements		
1	TR1	Pavement temperature		6	16	32
2	TR2	Underground temperature, -5 cm		6	16	32
3	TR3	Underground temperature, -10 cm		6	16	32
4	TR4	Underground temperature, -20 cm		6	16	32
5	TR5	Underground temperature, -50 cm		6	16	32
6	TA2	Temperature, 1.5 m		6	16	32
7	TD2	Dew point temperature, 1.5 m			16	32
8	TTy 850	Temperature, 850 mb (Yonago)			16	32
9	hhy 700	Altitude, 700 mb (Yonago)			16	32
10	hhy 500	Altitude, 500 mb (Yonago)			16	32
11	hhs 700	Altitude, 700 mb (Shionomisaki)			16	32
12	hhs 500	Altitude, 500 mb (Shionomisaki)			16	32
13	TTw 850	Temperature, 850 mb (Wajima)			16	32
14	hhw 700	Altitude, 700 mb (Wajima)			16	32
15	hhw 500	Altitude, 500 mb (Wajima)			16	32
16	TTw 500	Temperature, 500 mb (Wajima)			16	32
17	R	Radiation				32
18	Difference of temperature	TA1 (0.5 m) - TA2 (1.5 m)				32
19	TTs 850	Temperature, 850 mb (Shionomisaki)				32
20	Difference of altitude	hhy 700 - hhs 700				32
21	Difference of altitude	hhy 700 - hhw 700				32
22	Difference of altitude	hhs 700 - hhw 700				32
23	Difference of altitude	hhy 500 - hhs 500				32
24	Difference of altitude	hhy 500 - hhw 500				32
25	Difference of altitude	hhs 500 - hhw 500				32
26	Components of wind velocity	ffy 850 × cos ddy 850	dd = wind direction (angle)			32
27	Components of wind velocity	ffy 700 × cos ddy 700				32
28	Components of wind velocity	ffs 850 × cos dds 850				32
29	Components of wind velocity	ffw 850 × cos ddw 850				32
30	Hikone	Dew point temperature				32
31	Hikone	Wet bulb temperature				32
32	Hikone	Air temperature				32

Table 1 gives a harmonic analysis of diurnal fluctuation of road surface temperatures observed in Tsuru City along the Chuo Express Highway in fiscal 1967. Constants are classified according to weather.

Prediction Through Statistical Analysis

Structural fluctuation of pavement temperatures and spatial and time relationships among meteorological elements are understood from physical and meteorological concepts. On this basis, a statistical process can be applied to forecasting pavement temperatures. Two methods were examined for this purpose: multiple linear regression and categoric classification.

Prediction by Multiple Linear Regression Method—Among local and aerological data intimately related to the prediction of pavement temperatures, 180 elements were selected. Out of these, 32 elements were chosen as the most effective variates to form a 32-element regression formula. Discussion was also carried out on the basis of 16- or 6-element formulas from a practical point of view. Allocation of the variables of these multiple regression methods is given in Table 2.

This type of study is painstaking. It requires sorting through those factors most directly related to the physical phenomena that this system attempts to predict and arriving at a conclusion through a painful trial-and-error process. Moreover, the method of reaching a conclusion is necessarily dependent on a basic understanding of the mechanism appropriate for determining meteorological phenomena.

Spot observation data are sufficient for the short-period forecast of road surface temperatures. However, regional meteorological data are necessary in order to make reliable predictions, and aerological data are indispensable for long-period predictions.

Prediction of pavement temperatures, using the meteorological variables described, can be written in the following multiple linear regression formula:

$$Y = A_0 + \sum_{t=1}^{N} A_i X_i + \epsilon$$

where, in this case,

Y = road surface temperature to be predicted,
A_i = regression coefficient,
A_0 = constant,
X_i = value of variate observed at the time of prediction, and
N = number of dimensions.

Table 3 gives an example of regression coefficients obtained from a 16-element regression formula produced on the basis of observations at Hatasho along the Meishin Express Highway.

The standard deviation of errors involved in the multiple regression formula was computed in order to obtain more knowledge about the prediction accuracy. The errors originated in the 6- and 16-element regression formulas are shown in a sequence of time in Figure 6. Pavement temperatures were predicted by means of the road surface temperature predictor according to the 16-element regression formula. The prediction formula, worked out with data obtained during a winter season (60 forecasts), was applied in predicting pavement temperatures in the following winter. Actual results of the prediction (from 5:00 p.m. to 8:00 a.m. the next day) were 0.86 C in the mean error and 1.8 C in the standard deviation of error. A comparison of observations versus the results of forecasts with 6 and 16 elements is shown in Figure 7.

TABLE 3

REGRESSION COEFFICIENTS IN 1966 OBTAINED FROM 16-ELEMENT FORMULA

Constant	18:00	20:00	24:00	04:00	06:00	08:00
A_0	-4.8533	5.2374	-12.5220	-28.6821	-31.9767	-30.0362
A_1	1.1640	0.6687	0.2761	0.2009	-0.1699	-0.0519
A_2	-0.8531	-0.9415	-0.9358	-0.5689	-0.1629	0.3094
A_3	0.2797	0.8416	1.1168	0.4906	0.5204	-0.2913
A_4	0.3550	-0.0120	-0.2504	0.0492	-0.0839	0.2238
A_5	-0.0312	0.0398	0.0847	0.2330	0.2895	0.3423
A_6	0.0845	0.2290	0.3378	0.3364	0.3365	0.1928
A_7	0.0612	0.1864	0.2313	0.2164	0.2360	0.2003
A_8	-0.0012	-0.0891	-0.0883	-0.1408	-0.1281	-0.0442
A_9	0.0043	0.0011	0.0058	0.0095	0.0005	0.0179
A_{10}	0.0004	0.0054	-0.0020	-0.0003	0.0002	0.0000
A_{11}	0.0029	0.0015	0.0009	-0.0000	0.0023	-0.0003
A_{12}	-0.0034	-0.0043	0.0013	0.0035	0.0054	0.0075
A_{13}	-0.0051	0.0577	0.0824	0.1211	0.1038	0.0857
A_{14}	-0.0096	-0.0069	-0.0129	-0.0084	0.0051	0.0261
A_{15}	0.0049	0.0002	0.0062	0.0011	-0.0044	-0.0067
A_{16}	-0.0244	0.0303	-0.0042	0.0100	0.0099	-0.0008

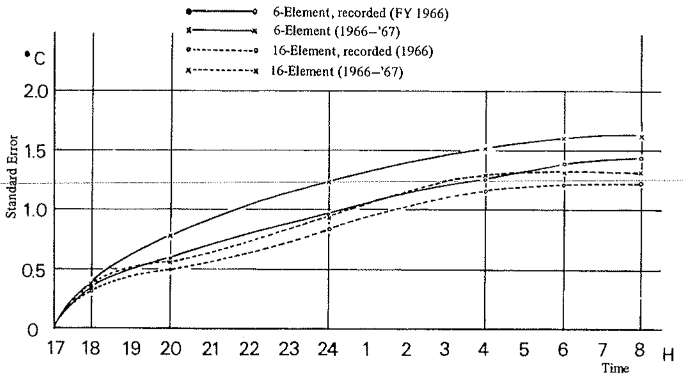

Figure 6. Standard deviation of errors.

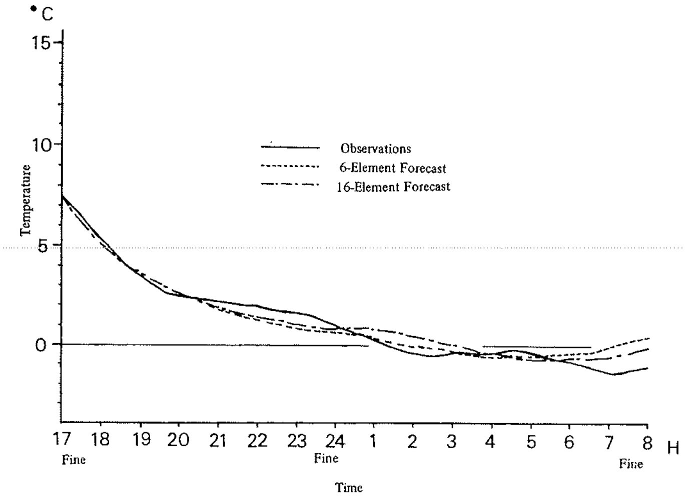

Figure 7. Prediction versus observations.

Prediction by Category Classification Method—In order to discriminate whether pavement temperatures fall below the freezing point, 5 elements including pavement temperature, underground temperature, air temperature, dew point temperature, and net radiation were chosen as prediction factors to allow a category classification of 5-dimensional space. This enabled discrimination and prediction of road icing according to category. The category classification is in this case a kind of discriminant analysis. A variate is divided at a point in order to discriminate which division an amount required belongs to. Accordingly, categories of $2^5 = 32$ are produced in the 5 dimensions. The classification points and groups in each category are determined by physical observation and by statistical treatment.

As an example, take 3 variates with prediction factors of x, y, and z. If the classification points of the prediction factor values are taken as x_0, y_0, and z_0 respectively, the number of categories classified are $2^3 = 8$.

1. $x \geq x_0,\ y \geq y_0,\ z \geq z_0$
2. $x \geq x_0,\ y \geq y_0,\ z < z_0$
3. $x \geq x_0,\ y < y_0,\ z \geq z_0$
4. $x \geq x_0,\ y < y_0,\ z < z_0$
5. $x < x_0,\ y \geq y_0,\ z \geq z_0$
6. $x < x_0,\ y \geq y_0,\ z < z_0$
7. $x < x_0,\ y < y_0,\ z \geq z_0$
8. $x < x_0,\ y < y_0,\ z < z_0$

TABLE 4

SKILL SCORE OF PREDICTIONS AT HATASHO, MEISHIN

Observed	Predicted		Total	Comment
	Above 0 C	Below 0 C		
Above 0 C	327	9	336	Short period prediction by time, every 2 hours, unit = 2 hours
Below 0 C	0	149	149	
Total	327	158	485	Skill score: 0.9571
Above 0 C	30	5	35	Short period prediction by day, unit = a night
Below 0 C	0	26	26	Skill score: 0.8324
Total	30	31	61	
Above 0 C	34	6	40	Long period prediction, 1967
Below 0 C	0	20	20	Skill score: 0.7750
Total	34	26	60	
Above 0 C	36	1	37	Long period prediction, 1968
Below 0 C	1	21	22	Skill score: 0.9275
Total	37	22	59	

If categories 4, 6, and 8 are taken as groups to reach the freezing point, they are predicted to reach the freezing point when the predicted time (x, y, and z) falls on 4 or 6 or 8. Other multidimensional category classification was conducted in this same way.

Table 4 gives a skill score that compares actual pavement temperatures with those that had been predicted. The first 2 cases are examples of short-range predictions within 2 to 4 hours, and the other 2 cases are long-range predictions from 5:00 p.m. to 8:00 a.m. the next day. In the latter cases, 2 variables of aerological data were added to the prediction factors. Rather good prediction results were achieved by using this method.

This sort of statistical prediction depends completely on the accuracy of the method applied. Moreover, meteorological data covering 2 to 3 years are necessary in order to provide stabilized forecasts with a minimum of errors.

CONCLUSION

Various methods have been examined empirically with specially designed simulators for each method to obtain an optimal prediction of pavement temperatures. It is very important that the temperature of paved surfaces be predicted automatically and mechanically without depending on meteorological knowledge if snow and ice on roads is to be effectively controlled. No practical inconvenience is presented by the alternative type of prediction of whether pavement temperatures, which are closely connected to road icing, fall below freezing point or not.

On this basis, the category classification method has been adopted as a means of making an objective prediction system of pavement temperatures. The system attained good results in its predictions, with skill scores of 0.775 in 1967 and 0.927 in 1968 for long-range predictions and 0.957 through 1967 and 1968 for short-range ones. The state of moisture on paved surfaces was detected accurately and reported to the control center.

The salient point of this system is not only to provide the men in charge of road maintenance with appropriate information but to alert drivers to the conditions by the warning signs. For this purpose, prior to the development of software that could ensure an effective system operation, surveys were carried out repeatedly on the distribution of temperatures on paved surfaces in road sections where snow and ice could be formed.

Informal Discussion

Glenn G. Balmer

Can you give us a little more detail on the moisture detector?

Inoue

We are making 3 kinds of observations: electrical conductivity measurements to detect surface moisture; scattering of light to determine the presence and state of surface moisture; and measurements of pavement temperature.

Balmer

What does the system cost?

Inoue

This system costs $300,000 per 40 km.

Ambrose Poulin

It seems to me that instead of looking at the entire heat balance equation for the surface affected, you could possibly use one or two sensors, which might give you practically all the information, and introduce logic into your computer program. Do you think that you could come up with a prediction system that instead of being 100 percent accurate and costing $300,000 might be 95 percent accurate and cost maybe $50,000 to $60,000? The point is, do you think that with one or two measurements, say surface temperature and the moisture condition, you could come up with the same information even though it might not be accurate 100 percent of the time?

Inoue

This might be possible.

Chesley J. Posey

Do you anticipate any problem from vandalism?

Inoue

We do not know.

Leonard H. Watkins

Along these 50 km where this system is installed, how many sensing stations are there? How far apart are they, and how do you determine their locations? Do you put them in known danger spots, or do you study the microclimate of the road?

Inoue

We have 30 of these different sensors in this 60-km section. The points are not the most dangerous because we studied the road surface with infrared telemeters and we know the performance of the road. The choice was based on the easiest point to maintain.

Thad M. Jones

How do you transmit the information from the individual meteorological station to the central control? Is it radio link or land line?

Inoue

We use cable, a telephone line.

Jones

Do the individual meteorological stations and warning signs have a power source independent of the main distribution 50-cycle current, or does the entire system require for its operation your regular power line voltage, or is it operated completely from batteries?

Inoue

We use a common commercial power source, not a special one, and the individual meteorological stations do not have standby power.

Don L. Spellman

I notice this system has a fairly new element, a direction and wind velocity indicator. How important is this in prediction of icing?

Inoue

In this system the radiation is a measured factor, and the wind direction and speed are secondary factors.

Balmer

On a second installation, would you install your stations as close as they are on this installation or would they be farther apart? For a 50-km section, would you have 7 stations, 3 stations, or 10 stations?

Inoue

If we installed a second system, the number of individual stations might be less than in this system. In this system we can accumulate the data, so the error can be reduced.

John A. Cook

At what height do you measure wind velocity?

Inoue

About 2 meters above the road surface.

Cook

Do you take into consideration dew point at the same time as you measure the wind velocity?

Inoue

It happens that dew point is important because of the radiation element of this point.

James A. Roberts

Do you have specific, significant evidence of the usefulness or effectiveness of the system in reducing accidents?

Inoue

We have had only one season and little experience with this system, but we have reduced traffic accidents markedly.

Prediction of Preferential Icing Conditions on Highway Bridges

C. Birnie, Jr., and W. E. Meyer

Preferential icing of bridges, i.e., the freezing of bridges before the approaches do, involves the interaction of a number of variables such as location, weather conditions, thermal properties of the bridge structure, and traffic density. This paper reports on research undertaken to correlate these variables of weather, geographic location, and bridge deck thermal properties that lead to preferential icing. A bridge deck over a stream was instrumented to gather data on a continuous basis throughout the winter of 1969 and 1970. The field study was supplemented with a computer simulation of the heat flux in bridge decks and with measurements on a deck section in the cold room. With representative weather data and knowledge of the thermal characteristics of the bridge structure, it should be possible to construct a probabilistic model to predict the number of days per year that icing will occur. Such a model will be useful to the highway engineer in devising an economically justifiable countermeasure.

Preferential icing of bridge decks, a well-known safety hazard, refers to the formation of ice on a bridge deck at times when the approaches become merely wet or even remain dry. The existence of this hazard is well recognized, but its seriousness and frequency of occurrence for a given bridge have not been investigated systematically. The factors that lead to preferential icing have not been subjected to scientific study, and the possible means for preventing it have not received the attention they deserve. Although much work has been done on the control of ice and snow on elevated structures, this has been solely as part of the overall removal operations. This paper is concerned specifically with the situation in which measures are required in a district only for some bridges and not for other bridges or roads and streets.

To deal with the problem, we need methods for assessing the frequency and severity of preferential icing of a given bridge, and an assessment of the feasibility of countermeasures. This paper is in the nature of a progress report because we cannot yet offer final answers to all questions. It attempts to offer an analysis of the problem and reports research under way at the Pennsylvania State University.

GENERAL CONSIDERATIONS

Preferential icing is caused by the difference between the thermal response of an elevated highway structure and that of the approachways to the local meteorological conditions. Preferential icing will occur when (a) the bridge deck surface is below 32 F and the approachway is not, and (b) moisture is available in the form of high relative humidity, mist, fog, rain, sleet, snow, or runoff from a snow bank or other source.

Given a meteorological cycle, can we predict whether a bridge deck will freeze? We have taken 3 approaches to obtain an answer to this question: (a) a numerical solution for determining the time-temperature history of the bridge surface for a specified ambient temperature cycle; (b) exposing a test slab in a controlled temperature room, simulating a bridge deck undergoing changes in ambient temperature; and (c) instrumenting a highway bridge.

The last approach is the most obvious one, but suffers from the drawbacks that preferential icing is an extremely transient phenomenon and that the frequency of icing is very much a function of local conditions. To select a suitable bridge, we examined 14 different ones. We knew that there were no records on the frequency of icing, but we also found that subjective information was not of very much help. Accident records were examined, but the information recorded is too ambiguous and reported accidents are statistically too infrequent to provide guidance. Therefore, we had to make our choice on the basis of inferred thermal characteristics and meteorological conditions at the site.

The experience with this search for a bridge that would make a good experimental site emphasized the importance of the other 2 approaches. A computer simulation would be of considerable value because it would help to clarify the relation between thermal characteristics of a bridge and its environment. Similar simulations have, of course, been done before (1). Our first simulation was a relatively simple one because it seemed essential to get some initial guidance for the other phases of our work. There is a purely analytical solution with limited boundary conditions for the heat transfer problem in a slab (2). Because, however, the primary variable in the problem is the nature of the varying heat transfer conditions at the slab surfaces, a numerical approach was adopted. The computer program (SIMULATION I) solves the heat conduction equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t}$$

for a one-dimensional slab with heat flow only in the direction perpendicular to the surfaces for the temperature distribution in the slab as a function of time.

LABORATORY EXPERIMENTS

We constructed a test slab to simulate a typical prestressed concrete bridge deck. Originally we intended to do this outside near our laboratory. This would, in effect, have brought a bridge to a location where observations and measurements could be made frequently, conveniently, and in comfort and safety. Although useful for many purposes, the test cycles would still have been largely dictated by nature. On the other hand, certain effects that influence preferential icing in the field would have been absent and difficult to simulate realistically, for instance, the residual effects of anti-icing agents. Therefore, we decided to place the slab in an available cold room and treat it purely as a laboratory tool, rather than as a substitute field experiment.

With the slab in the cold room, temperature, humidity, and precipitation can be controlled. Instrumentation can be checked out and, if necessary, put through repeated identical test cycles. This applies specifically to ice detection systems and methods. Eventually countermeasures can be evaluated with it before being incorporated in expensive field installations. In addition, the computer simulation can be validated with the slab.

Figure 1 shows a top view of the test slab in place. It is 3 by 4 ft with a thickness of 7.5 in., poured of Class AA concrete and insulated on its sides with Styrofoam to minimize end effects. Reinforcing rods were placed within the slab, their size and spacing approximating those in actual bridge decks. The thickness of the slab was selected to correspond to that of the bridge deck selected for the field experiment. Approximately 50 copper-constantan thermocouples were located at various points within the slab. Figure 2 shows a cross section of the slab and the location of these thermocouples. In addition, a wood plug 4 in. in diameter was placed in

Figure 1. Top view of laboratory slab installed in cold room.

the slab when it was poured. It was subsequently replaced by a concrete cylinder containing thermocouples at ½ in. depth intervals. The slab was set up on concrete blocks to allow air to circulate over and under it. Styrofoam pads were placed between the blocks and the slab to thermally isolate it from the supports.

The thermocouples distributed through the slab provided the following information: There are no significant end effects; the reinforcing rods do not significantly affect the temperature field; and the couples in the core indicate the same vertical temperature gradients as couples elsewhere in the slab.

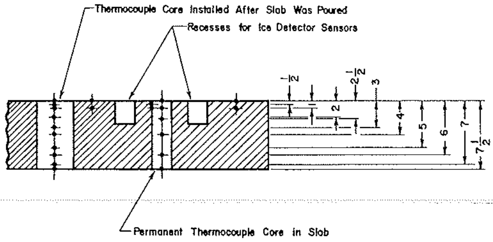

Figure 2. Cross section of laboratory slab showing location of thermocouples.

COMPUTER SIMULATION

The computer program (SIMULATION I) will be described in a forthcoming report (3). Figure 3 shows the computed and experimental values under identical thermal conditions. The agreement is good and was achieved by only manipulating the upper and lower surface film coefficients in the program. The actual values of the test slab coefficients are not known. This is significant in that it points out that if the computer simulation is to predict temperature distributions reliably, data on bridge deck surface film coefficients must be obtained. Williamson (4) has done some work in this area, but for our purposes more detailed information will be necessary than Williamson's work provides.

Another example of the usefulness of the program is shown in Figure 4 These results were obtained by first representing the ambient air temperature change by a polynomial that allowed the temperature to fall from an initial value of 77 to 10 F over a 4-hour period. The temperature in the slab was initially set at 77 F throughout. The program was run first allowing both the upper and lower ambient temperatures to fall as they would on a bridge deck, with both sides exposed to the same ambient conditions. The program was then rerun with identical initial conditions, but with the bottom surface held at 77 F, thus simulating an approachway receiving heat from the subbase. Several runs were made in these 2 modes but with varying surface film coefficients. Figure 4 shows that the lower the surface film coefficient, the longer the period of potential preferential icing will be.

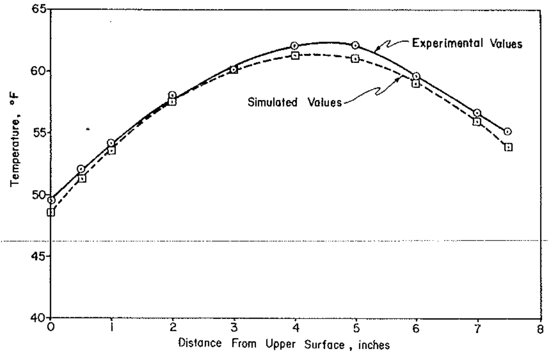

Figure 3. Comparison of temperature gradients in laboratory slab as measured and as computed by SIMULATION I.

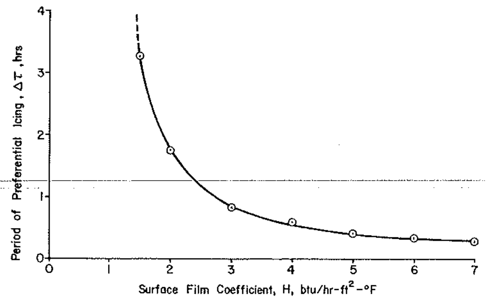

Figure 4. Period during which bridge deck is below freezing while approachway is not, as function of surface film coefficient (SIMULATION I).

The program is now being refined (SIMULATION II) to add simulation of multilayer decks and internal heat sources. The film coefficients are handled by a subprogram that will also take care of radiation heat losses or gains. The subprogram in effect controls the total heat fluxes at both surfaces. These heat fluxes are, of course, influenced by numerous variables. The experiments will serve to derive manageable functions.

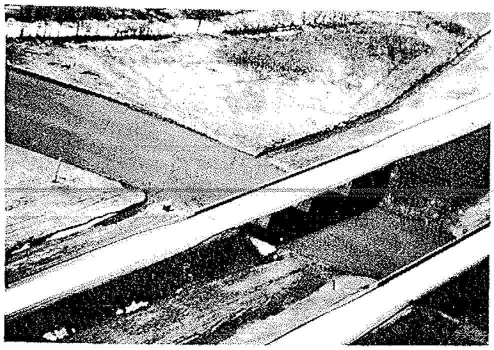

Figure 5. Aerial view of I-80 bridge over Bald Eagle Creek in Centre County. Upper deck is instrumented; instrument shack is on near creek bank just above bridge.

BRIDGE SURVEILLANCE

Interstate 80 bridge across Bald Eagle Creek in Centre County, Pennsylvania, was selected as the field test site (Fig. 5). The bridge is constructed of 7.5-in. thick slabs supported on concrete box beams. Installing thermocouples directly in the existing deck would have been extremely difficult. Because the experiments with the laboratory slab had shown that thermocouples in a removable core give temperature readings equivalent to those in the slab itself, a 4-in. diameter hole was cut into the deck and a core with thermocouples in place inserted into it (Fig. 6). This is a most convenient and economical method, particularly because surveillance would suffer only a brief interruption if one or more thermocouples should fail.

A similar core was installed in the approach to the bridge. The temperature profiles in both cores are recorded continuously. Moisture sensors were also installed in the deck to detect ice. A complete meteorological station was installed at the bridge site to monitor air temperature, wind speed and direction, precipitation rate, and absolute and relative humidity. The general arrangement of the instruments is shown in Figure 7. The recorders and auxiliary equipment are housed in a shack adjacent to the site. Figure 8 shows an inside view of the shack.

This installation will provide information on (a) the frequency and duration of the periods when the bridge surface is below 32 F but the approachway is not, (b) the ambient conditions during and preceding these periods, (c) the frequency with which moisture to cause preferential icing is available , and (d) the source of the moisture.

We have not yet found a method that is totally satisfactory for detecting the presence of ice on the road surface. We need to know when temperature and moisture combine anywhere on the bridge deck to form ice, and whether the ice constitutes a traffic hazard.

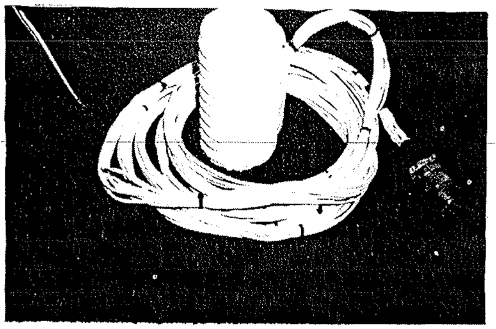

Figure 6. Core with thermocouples ready for installation in deck of bridge.

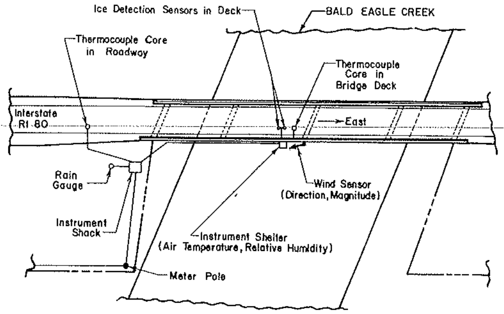

Figure 7. Plan view of instrumented bridge deck showing sensor locations.

ICE DETECTION METHODS

Detection methods can be grouped into 3 major categories:

1. Warning systems generate a suitable signal to warn traffic that ice is present on the bridge. When the condition ceases to exist, the signal will terminate.
2. Countermeasure actuation systems generate a signal that anticipates that ice will be forming sometime in the future. The length of lead time will depend on the type of countermeasure and may also depend on the specific weather conditions.
3. Monitoring systems monitor the functioning of the other 2 systems and contribute to research. Their accuracy must be high, and they should be capable of monitoring the entire test surface.

Commercial systems are either the first or the second type. They monitor one or more of the variables, air temperature, road surface temperature, road surface moisture (liquid or frozen), and relative humidity. Those systems whose primary function is to anticipate icing conditions usually rely on the detection of air temperature and relative humidity because, when the air temperature approaches 32 F and the relative humidity is above 95 percent, the possibility of surface icing is high. The reliability of such systems has been shown to be doubtful (5). For example, such a method will not detect water resulting from melting snow or ice running across the road and about to refreeze.

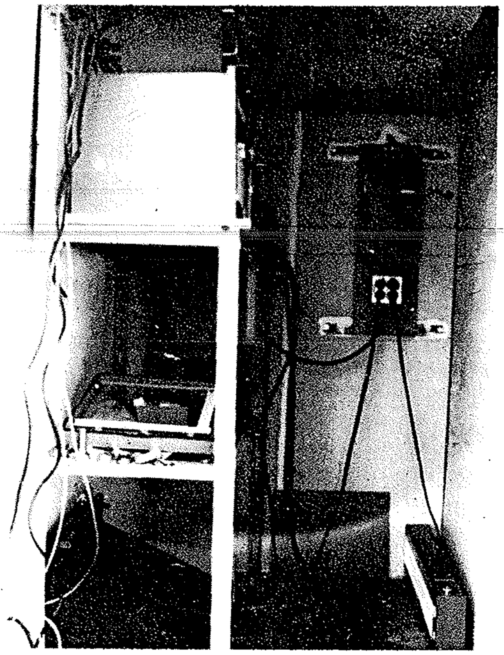

Figure 8. Inside of instrument shack.

Most of the current commercial systems do in fact monitor surface moisture in addition to air temperature and local relative humidity. Commonly 2 adjacent sensors measure electrical conductivity at the road surface. One of the sensors is heated. If the surface is dry, both sensors show high and equal resistance; if the surface is wet, both sensors have low and equal resistance. If there is ice on the pavement, the resistance of the unheated sensor will be high because it is covered with ice, which has high resistivity, while the heated sensor will melt the ice and low resistance will be indicated. Tests (5) indicate that this is a fairly reliable method, but conditions can exist under which it will generate a false signal. Figure 9 shows a laboratory experiment in which a thin film of ice was deposited on the test slab by a supersaturated atmosphere. An ice film has formed over the unheated sensor. The heated sensor, however, is dry. Evidently the energy input is great enough not only to melt the ice but also to evaporate all moisture from the sensor surface.

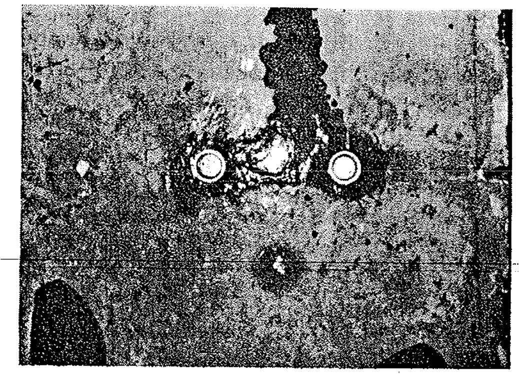

Figure 9. Ice detector sensors in laboratory slab when atmosphere is supersaturated. Left (unheated) sensor is covered with ice film, and right (heated) sensor is dry.

For practical applications, failure of a detecting system to deal with such subtleties may not be important, but for research purposes it is, because we must have accurate and reliable records of when ice formation began and when the ice disappeared. In addition, a research system should monitor not merely a small spot but the entire area under surveillance. Freezing meltwater may miss a spot sensor, and channeled traffic may melt the ice over the sensor while outside the wheelpaths ice may remain.

Another problem is the relation between the presence of ice and slipperiness. What we really are trying to eliminate is "preferential slipperiness." On the laboratory slab friction measurements were made at various ice thicknesses with a Keystone-Penn State drag tester (6). With films of ice not thick enough to obliterate the surface irregularities, the surface was not found to be especially slippery.

At present a conventional pavement ice detector is being used on the test bridge deck. The continuous on-off records from it are supplemented by daily reports from all highway maintenance personnel passing over the bridge. When icing conditions prevail, project personnel make an inspection whenever possible. We are, however, continuing our search for a fully automatic method that will give 100 percent coverage in time and space with as close to 100 percent accuracy as possible.

We have considered numerous detection schemes and tried out several, such as radiometric, light reflective scanning, and photography. We have also given thought to methods of automatically measuring slipperiness. So far all these solutions have been found to have serious shortcomings.

COUNTERMEASURES

Many methods for keeping roadways free of ice and snow have been investigated or used on a limited scale over the past 20 years. The prevention of preferential bridge icing could utilize this technology, except that the boundary conditions for its use are different. Melting a 6-in. snowfall competes economically with its removal by plowing. Control of preferential ice on bridges is in most cases an added service. On the other hand its accident potential is thought to be very high because it represents a local hazard that traffic encounters without warning under otherwise normal conditions.

Experience shows that the frequency with which bridges may freeze before roadway varies considerably. Obviously, economic considerations dictate different solutions when a countermeasure is likely to be used only once a year and when it is needed frequently, or when the skidding accident experience is high because of either traffic density or road geometry.

Operating cost is an important factor with snow melting schemes, but not with methods for the prevention of preferential icing because very low power levels are sufficient inasmuch as the object is only to prevent slippery conditions on the bridge when these do not exist on the adjoining roadway. Thus capital cost becomes extremely important.

THE PROBLEM OF PREDICTION

The crucial problem is to determine what level of service a particular bridge requires and how this service can be provided at acceptable cost. Although there are secondary factors, the requirements are functions of the thermal properties of the bridge and of its climatic environment. Rapid methods are needed to determine these 2 factors for a large number of bridges.

The thermal properties of a bridge are essentially constant and can therefore be determined at any time of the year. In essence this requires determining the effect of a known rate of input or subtraction of heat. There are numerous ways in which this can be done. We are currently using a vehicular-mounted radiometer to measure surface temperature while in motion. Knowing the surface temperature of the bridge deck and the adjoining roadway as well as the ambient temperature, we should at least be able to make a rough classification of bridges. Further measurements may be needed to characterize bridges that are subject to potential preferential icing.

The environmental characteristics are more difficult to quantify and describe. Macrometeorological data provide not much more than an envelope and a base line. Practical methods must be found for relating the microclimate at the bridge with the macroclimate reported by the U.S. Weather Bureau. The experience with our instrumented bridge should provide insight into the principles to be applied. We expect to find classifiable weather cycles for the near-freezing temperature range to which a limited set of rules can be applied for predicting at least the difference in the surface temperatures of bridge and approachway.

CONCLUSIONS

The problem of predicting when preferential icing of bridge decks will or will not occur is a complex one. Given a known environmental cycle, it is possible to predict the temperature differences between bridge deck and approachway provided the thermal characteristics of both are known. Possibilities have been indicated for obtaining these characteristics by routine methods. (Not mentioned was the prediction of the thermal characteristics of a bridge while in design, but guidance for a practical procedure for this purpose should be obtainable from the experience with existing bridges.)

The climatic conditions that can lead to preferential icing must be obtained by establishing a relationship between the macrometeorological histories that the U. S. Weather Bureau can provide and the microclimate at the bridge. At this time only speculations can be offered as to the type of data that must be collected at the bridge site and over what period. The instrumented test bridge is expected to furnish this type of information, at least for a single location.

Countermeasures will no doubt differ greatly, depending on the probable frequency with which preferential icing is likely to occur. Because different countermeasures require different phasing between actuating signal and arrival of the icing conditions, we must be able to predict from the ambient changes when icing is likely to occur.

ACKNOWLEDGMENTS

The research on which this paper is based is being performed in cooperation with the Pennsylvania Department of Highways and the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. The authors appreciate the assistance and cooperation from various offices and individuals of the Department of Highways, in particular from the project coordinator William G. Weber, Jr. The contribution by several companies of equipment, material, and advice is gratefully acknowledged. Tajin Kuo developed SIMULATION I, and David Biss prepared and conducted the laboratory and field experiments. The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the Pennsylvania Department of Highways or the Bureau of Public Roads.

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Formal Discussion

W. D. Glauz and R. R. Blackburn

Birnie and Meyer are to be complimented on their many faceted approach to the examination of an illusive problem—detecting or predicting the occurrence of localized icy conditions on bridge decks. Their use of analytical and laboratory findings in conjunction with field work is commendable. However, there are certain features of bridge icing that, although alluded to, have been underestimated by the authors.

There are 2 major situations under which localized bridge icing might occur: (a) the freezing of some form of precipitation and (b) the occurrence of frost. In addition, bridge deck cooling is caused by both convection and radiation. The occurrence of frost is most often influenced by radiation cooling, whereas the freezing of precipitants can occur as a result of either type of cooling.

Let us first examine the icing condition studied by Birnie and Meyer—freezing precipitation in conjunction with convection cooling. We consider first the heat transfer behavior of the approach roadway. Heat can be lost from the upper surface to the adjacent air by the mechanism of convection, which is strongly dependent on surface winds that provide the movement of cooler air across the pavement. At the same time, heat is supplied to the pavement from below by conduction of heat from the warmer ground beneath the roadway. The net rate of temperature change, therefore, is dependent on the 2 heat-transfer rates.

A bridge, however, is not endowed with a heat source underneath. In fact, during a period involving cold winds, the bridge may lose heat by convection from both upper and lower surfaces. Thus, during a period of decreasing air temperatures, the bridge temperature is likely to be lower than the adjacent road temperature but warmer than the air temperature. If this occurs in conjunction with, or is followed by, a period of freezing rain, drizzle, sleet, or fog, quite likely the bridge will become icy whereas the approach roadway will only become wet. The temperature differential between bridge and approach roadway can be even greater if the neighboring terrain is such to enable higher wind velocities over the bridge; this is often the case because the bridge is elevated and thus less influenced by the earth's surface boundary layer.

The mechanism of bridge frosting is somewhat different and, in many locales, more prevalent than the phenomena just discussed. It requires the bridge deck temperature to be lower than the dew point temperature of the local atmosphere, which, in turn, is normally lower than the air temperature. In practice, a very high local relative humidity is also required—a common occurrence near rivers and other bodies of water. Under these conditions, the moisture in the air, when it comes in contact with the colder surface, will condense. If the deck temperature also happens to be below the freezing point, the condensation will be in the form of ice crystals.

The bridge deck-air temperature differential is occasioned by heat loss due to radiation. This generally occurs at night under clear skies when radiation can occur to the essentially absolute zero temperature of outer space. In this situation the bridge will tend to gain heat by convection from the warmer air, again depending on wind speeds. Here, then, a very calm atmosphere (lack of wind) will lead to lower deck temperatures. The approach roadway also radiates in the same fashion but is aided, again, by the warmer ground below.

The choice of surface film coefficients used by Birnie and Meyer, both for the analytical work as well as the chamber experiments, is therefore primarily dependent on wind speed when convection is being considered. Radiation heat losses, on the other hand, cannot be expressed in terms of a surface film coefficient. Thus their analytical model should not be expected to yield realistic, nonempirical results. Likewise, some difficulty might be experienced with the laboratory experiments because the simulation of winds may be a problem and the simulation of the radiation heat losses may be nearly impossible.

Birnie and Meyer

The authors appreciate the comments made by Glauz and Blackburn. These are all valid and had been given some consideration although not specifically referred to in the paper.

The significance of the subgrade as a source of heat to the roadway is recognized. It is believed that this will be especially significant during the fall months when the average daily temperature is falling. Originally it was not planned to measure temperatures below the 7.5-in. level in the bridge approachway. However, at the time of thermocouple installation a probe was placed at a depth of 2 ft in order to monitor the subgrade temperature.

The possibility of frost formation as a source of slipperiness on the bridge was one of the major factors in the choice of the test site. The stream flowing under the bridge stays relatively warm all year because of the location of a power station about 2 miles upstream. We felt that this would furnish ideal conditions for frosting. However, the observations for one winter, which admittedly are limited, have not indicated any preferential frosting. On several occasions at very low air temperature, warm moist air was observed rising from the stream and forming hoar frost on surrounding vegetation and fences but not on the bridge deck. Furthermore, studies in the laboratory indicate that frost on a surface is not necessarily slippery unless it is quite heavy. Frost was allowed to form on the test slab by creating a supersaturated atmosphere and allowing it to condense. The slipperiness of the surface was then checked using a hand skid tester. Very little change in skid resistance was noted over that of a set surface. Apparently the surface disparities are great enough to nullify any effects of the frost when the layer is thin. More precise tests should be run to establish the correlation between frost layer thickness and skid resistance.

The net exchange of radiant energy between road surface and sky is important. Preliminary field data indicate that the surface emissivity has a major effect on the surface temperature. As expected this is most notable on clear days and nights. The radiant energy effect was also noted during laboratory tests when a strong light was used for illumination when taking pictures. It was noted that the ice in the region struck by the light rapidly melted. In developing the computer simulation, we included a term for radiant energy in the surface equations. At the time this paper was written, values had not been assigned to this parameter because we were uncertain as to what magnitude could be considered as reasonable. Consideration is also being given to placing instrumentation at the test site for measuring the net radiation exchange.

The Profiling Radioactive Snow Gage

James L. Smith, Howard G. Halverson, and Ronald A. Jones

Determination of snowfall amount or whether snow is actually falling is a major problem for agencies involved in snow removal or control on remote mountain roads or on remote, unattended airfields. A system has been developed by which snow density and depth may be measured in ½-in. increments by vertical profiling of a snowpack. The system is highly accurate and may be adapted for remote operation. With it one may determine whether snow is falling, the intensity of snowfall, the depth of the snowpack, and its density at all points in the pack. One may also determine whether rain is falling onto a pack, when the rain ceases, and when snow begins to fall again. Pack settlement, melt, or ice-crust formation may also be monitored. The gage consists of a small radioactive source and a detector that are drawn at a rate of one foot per minute through two access tubes extending from ground line to a point above the highest snow deposition. The signal can be sent by telephone line or radio to a base station where the signal is converted to depth and density and is recorded.

One-third of the earth's land surface is covered by snow and ice (1). Most of the great river systems of the world depend on snowmelt water for their flows. Water for the arid regions comes largely from melted snow; in California, 51 percent of all streamflow is derived from melted snow. Some of the most disastrous floods in the United States come from snowpacks melting too rapidly or from rain falling on and melting snowpacks.

Large snowfalls are the most frequent cause of paralysis of transportation systems. These result in highway closures because of poor visibility, avalanches, or snow that accumulates faster than available equipment can remove it from the roadway.

Few resources are so extensive in area, so disruptive to transportation, so useful and yet so threatening to man as snow.

With so extensive and important a resource one would expect that man would have devised reliable systems for monitoring rates of snowfall, snow depth, and snow condition. Likewise one would expect to find a large array of formulas with which to predict the reaction of snow on the ground to environmental stimulii that cause snow to melt. Such is not the case.

Three basic forms of snow measurement have been used to date. The first, and most extensively used method, consists of one or more of the extraction or gravimetric techniques. The second, and currently popular, method makes use of a weighing system. The third, a recent innovation, uses isotope snow gages.

Most snow surveys are taken by men traveling to the snow course in the mountains and taking gravimetric samples. Hand sampling consists of driving a hollow tube into the snowpack, extracting the tube and the included snowcore, and determining the weight of the column of snow. Knowing the length of the sample and its weight, a snow surveyor can compute water content and density with an error of ±7 to ±12 percent (2, 3). Such a system is costly, destroys the sampling site, and is not usable for studying in situ changes of the pack structure.

Beaumont (4) suggested the practicality of determining the snow water equivalent with a weighing system. He proposed using a 12-ft (3.66 m) diameter butyl rubber pillow filled with methyl alcohol and installed on the ground prior to snowfall. As the snow falls on the pillow, the internal pressure is increased. The pressure is related to the mass, or weight, of the snow above it. A manometer or a pressure transducer is used to measure this pressure.

A large number of pressure pillows have been installed in the mountains of the western part of the United States. Results from their use have varied widely. We suspect that success or failure is dependent on the location of the pillow and the reaction of the snow to the environment. Snow bridging, resulting from ice lens formation, appears to disrupt the downward displacement of weight onto the pillow from the overlying snow. Measurements taken during such periods are inaccurate. Where there is no ice lensing the pillows appear to react correctly to weight changes in the snowpack.

Development of the first nuclear snow gage was reported by Gerdel et al. in 1950 (5). This gage used a cobalt-60 radioactive source at ground level with a detector positioned above the snow. The readout of this gage was a single number translatable to the water equivalent of the snowpack between the detector and the source. Since this first study there has been a constant effort to develop a better nuclear gage (6, 7).

The neutron single probe system utilizing the scatter principle from a radium-beryllium source encapsulated with a boron trifluoride gas detector tube was the first radioactive system used to profile snowpacks (8, 9). Density may be determined in approximately 6-in. (15.24 cm) vertical increments with an accuracy of ±2 percent (10). The density of thin ice lenses common to the snowpacks of the Sierra Nevada of California could not be measured. Multiple calibration lines were also necessary in order to accurately measure density near the snow-air and snow-soil interfaces.

DEVELOPMENT OF THE PROFILING SNOW GAGE

As populations expand, water needs expand, while the total supply of water remains the same. Thus it becomes necessary to increase downstream water recovery of as much of the melting snow as possible. This necessitates better control of snowpacks in lands lying above reservoirs so that melt rate may be accelerated or decelerated to secure better utilization of reservoir space. As man intensifies his activities on the flood plains of rivers, flood control agencies need improved systems of warning that will permit more time to evacuate people from the flood zones.

Present systems of snowmelt forecasting are based on lysimeter studies of net water draining from the pack. Surface melt is held in the pack until sufficient water has been generated to flow through the pack. With present prediction equations, one is unable to accurately forecast future reaction of the snowpack to rain-on-snow or other melt-producing factors. More precise study and monitoring of snowpacks require a system for measuring in situ change in the internal snowpack structure with changes in time.

The profiling snow gage was developed to accomplish this goal. The first profiling radioactive gamma transmission snow gage was tested with both Geiger-Mueller and scintillation detectors in 1964. The successful use of the gage during the winter of 1964-1965 was reported by Smith et al. in 1965 and 1967 (11, 12). Since development of this first profiling gage, slight variations of this system were installed by the Agricultural Research Service, U. S. Department of Agriculture, in Vermont, by Amarocho and Espildora in Chile (13), and by Guillot et al. in France (14).

The CSSL gage consists of 3 units: density sensor, lift unit, and signal conditioning and recording system (Fig. 1).

The density sensor includes a 10 mc ^{137}Cs source and a scintillation detector horizontally suspended in 2 parallel access tubes that extend vertically from below ground to a height greater than the maximum anticipated snow accumulation. The access tubes are set 26.25 in. (66.67 cm) apart. The inside diameter of the source and detector access tubes are 0.75 in. (1.90 cm) and 2.00 in. (5.08 cm) respectively. The scintillation detector is a sodium iodide (thallium-activated) crystal 1.50 in. (3.81 cm) in diameter and 0.5 in. (1.27 cm) thick. The crystal is attached to a photomultiplier tube. Both are sealed in a cylindrical aluminum case. The photomultiplier signal is transmitted by a coiled cable to a preamplifier housed in the lift unit.

The lift unit consists of 2 reels connected by a drive shaft (Fig. 2). One spool is positioned at the top of each of the parallel access tubes. Power is provided by a 1.25-hp dc electric motor. Steel cables from the reels are connected to both the source and

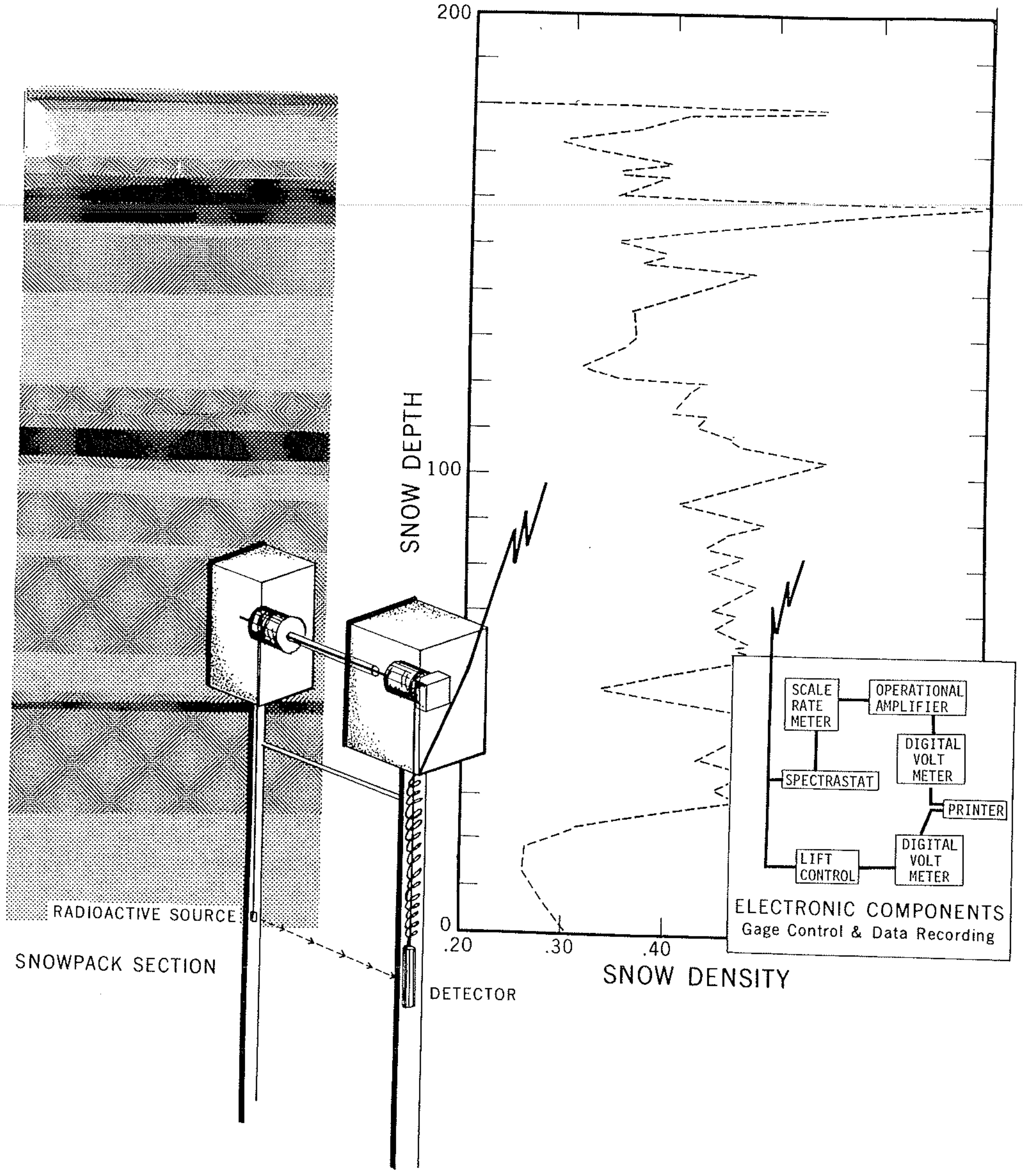
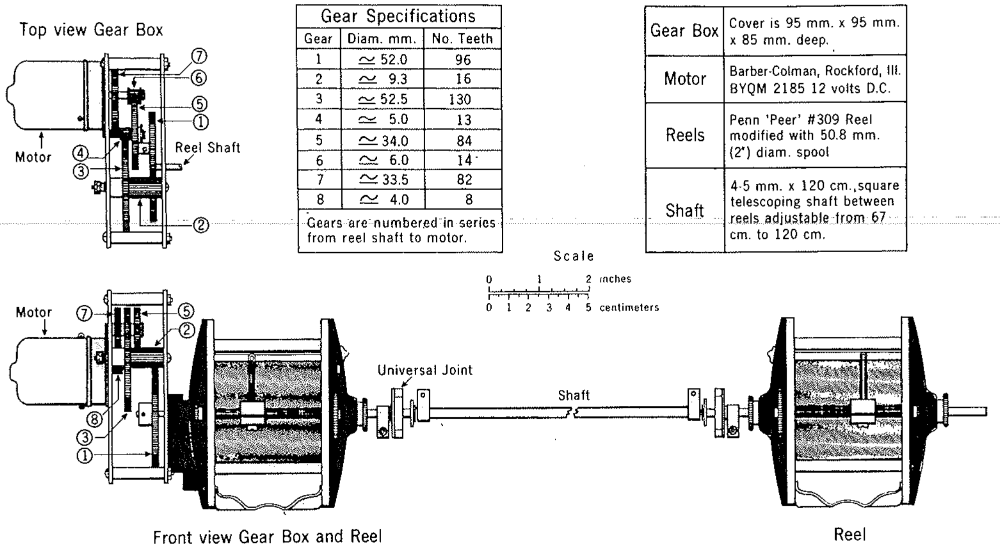


Figure 1. Profiling nuclear snow gage consists of source-detector, lift unit, and signal conditioning and recording system.

detector. The lift unit moves the source and detector at a rate of 12 in. (30.48 cm) per minute.

A secondary circuit within the lift unit indicates the position of the source-detector above or below ground level. A voltage divider is geared to the drive train and counts the revolutions of the reel spools. When a potential is applied, the source-detector position can be read from the transducer.

The signal conditioning and recording unit receives the signal from the preamplifier tube via a 250-ft (76.20 m) coaxial cable. The incoming signal is transferred to a peak-stabilized pulse-height analyzer. Gamma photons from the cesium-137 source constantly emit at their photo-peak energy into the snowpack in all directions from the



Gear Specifications

Gear	Diam. mm.	No. Teeth
1	≃ 52.0	96
2	≃ 9.3	16
3	≃ 52.5	130
4	≃ 5.0	13
5	≃ 34.0	84
6	≃ 6.0	14
7	≃ 33.5	82
8	≃ 4.0	8

Gears are numbered in series from reel shaft to motor.

Gear Box	Cover is 95 mm. x 95 mm. x 85 mm. deep.
Motor	Barber-Colman, Rockford, Ill. BYQM 2185 12 volts D.C.
Reels	Penn 'Peer' #309 Reel modified with 50.8 mm. (2") diam. spool
Shaft	4-5 mm. x 120 cm., square telescoping shaft between reels adjustable from 67 cm. to 120 cm.

Figure 2. Lift unit consists of 2 modified fishing reels, connecting shaft, reduction gears, and motor.

source. When they collide with the electron field of the surrounding snow, some are backscattered. Some travel through the snowpack to the detector without collision and thus without loss of energy. All gamma photons striking the crystal, both backscattered and full-energy photons, create output pulse amplitudes from the photomultiplier proportional to their impact energy. A pulse-height analyzer whose window is set at the photo peak of cesium-137 receives all impulses, but passes only those in the photo-peak energy level. These are proportional to the density of the material being studied. The vertical width of the band "seen" is a function of the thickness of the NaI crystal, the rate of profiling, and the time constant of the rate-meter circuit. The pulse-height analyzer by constant searching and recentering on the photo-peak eliminates electronic drift of the photomultiplier that is caused by temperature changes in the detector tube.

From the pulse-height analyzer the signal goes to a rate-meter circuit with a $2\frac{1}{2}$-second time constant. This is sufficient to "smooth out" the random nature of the cesium disintegration. An analog signal from the rate meter is cabled to an operational amplifier circuit, which converts the signal to density (g/cm^3). The signal is digitized and transferred to one channel of a 2-channel printer. It may be placed onto magnetic tape if desired.

The depth indicating circuit in the lift unit provides a simultaneous reading with each density reading. An analog-to-digital converter is placed in parallel with the one digitizing density readings. Digital depth information is transferred to the second channel on the printer. Depth and density are printed simultaneously at a selected interval. The interval between density readings can be set by adjusting the sampling rate of the voltmeter-printer combination. The interval now used is 0.03 to 0.05 ft (0.9 to 1.52 cm). A computer program has been written to take this information and transform it into a $\frac{1}{2}$-in. (1.27 cm) thick incremental profile of depth, density, and water content, with calculations of total depth, average density, and total water content of the snowpack.

The signal conditioning unit provides power to the lift unit with a provision to reverse the direction of travel of the source-detector. Voltage for the depth indicator is also provided. These signals are connected to the lift unit with a separate cable.

CALIBRATION OF THE SYSTEM

The source and detector are stored underground in the access tubes when the gage is not being operated. When in the storage position, source and detector are separated by a hollow box containing a sheet lead standard. The transmission of gamma energy through this standard is equated to the equivalent of 26.25 in. (66.67 cm) of homogeneous material. During profiling, transmitted energy coming through the snow is taken as a percentage of energy that passed through the standard, and, through use of the operational amplifier, the actual density of the snow in g/cm^3 is printed on paper tape.

The calibration equation is

$$\rho = C - b\left(\log \frac{\text{count} \times 100}{\text{standard count}}\right)$$

where

ρ = snow density in g/cm^3,
C = constant ≃ 1.300 to 1.700, and
b = slope ≃ 0.500 to 0.700.

Note: C and b vary with different standards.

A calibration graph is obtained by taking gamma transmission readings through a series of uniform-density 2¼-in. (5.72 cm) thick polyethylene blocks. The more blocks used, the higher will be the known equivalent snow density being measured. Relation between the polyethylene blocks and snow density was determined theoretically and by gravimetric sampling of known quantities of water, ice, and snow. Plotting output count over equivalent snow density produces a straight-line graph on semilog paper. The slope and intercept of the line are calculated and used as constant factors in the operational amplifier density circuit. Regression analysis indicated that snow density can be determined with a standard error of ±0.015 g/cm^3 in the range 0.001 to 0.686 g/cm^3.

Melt of the snow around the access tubes is another possible source of error. We have found the effect of suncupping to be insignificant except at the end of the snow season. By this time general snow cover is discontinuous over the watershed. This condition creates more error in snowmelt prediction than that induced by suncups around the access tubes. We do not consider melt around the tubes as significant provided tube diameters do not exceed present sizes.

INFORMATION AVAILABLE WITH PROFILING SNOW GAGE

With the gamma-transmission profiling snow gage, one may measure 8 factors important to understanding snow hydrology: total snow depth; snow density at ⅓- to ½-in. increments throughout the pack, and the average density of the entire pack; total water content of the pack; water content increase or decrease and the section of the pack where the changes are occurring; amount of snow that has fallen since the last measurement; rainfall amount and intensity until such time as the snowpack begins to discharge water; melt rate between measurements if melt is occurring; and moisture changes in the soil (with a closer source-detector spacing).

Since 1964 we have measured snow density with the profiling snow gage at intervals varying from once to several times per day. In addition, we have studied water movement through snowpacks from snowmelt, from natural rain falling on snowpacks, and from artificially applied rain on snow. New theories about water-holding capacities of snow, water transmission rates, and the factors affecting water transmission have come from these studies (15).

The following case histories serve as illustrations of the utility of the snow gage.

1. Melt rate of a pack can be determined. On March 29, 1966, 3 profiles were made at 8:40 a.m., 1:25 p.m., and 5:11 p.m., Pacific standard time (Fig. 3). Pack depth decreased by 1 in. (2.54 cm). The melt water moving through the pack can be seen as increased density of the 2 latter profiles over the 8:40 a.m. profile.

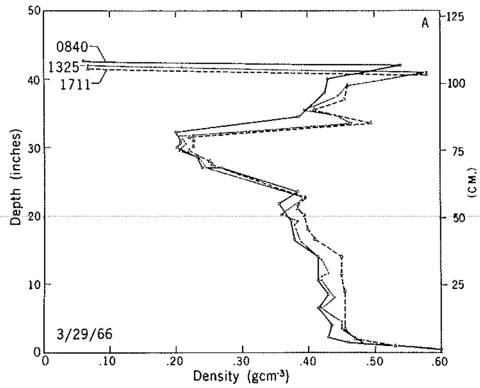


Figure 3. Three profiles of same snowpack showing melt. Note the 2 ice lenses at surface and at 33-in. depth.

2. Compaction and settling of the snowpack can be determined. This is shown in Figure 4. A 27-in. (68.58 cm) layer of 10 percent density snow, overlaid by a 5-in. (12.70 cm) layer of 23 percent density snow, was able to support an overburden of 20 in. (50.80 cm) of approximately 12 percent density snow. Snowfalls during the following 4 days increased the density of the entire mass. Density of the 27-in. (68.58 cm) layer increased progressively from 10 to 25 percent.

Density alone is not always a reliable index of snow strength. Air temperature increase can cause snowmelt and structural alteration and thus decrease strength. However, a higher density snow will usually have a higher strength (16). It may be possible to estimate the strength of snow by analyzing the history of density changes recorded by the snow gage in conjunction with the meteorological record.

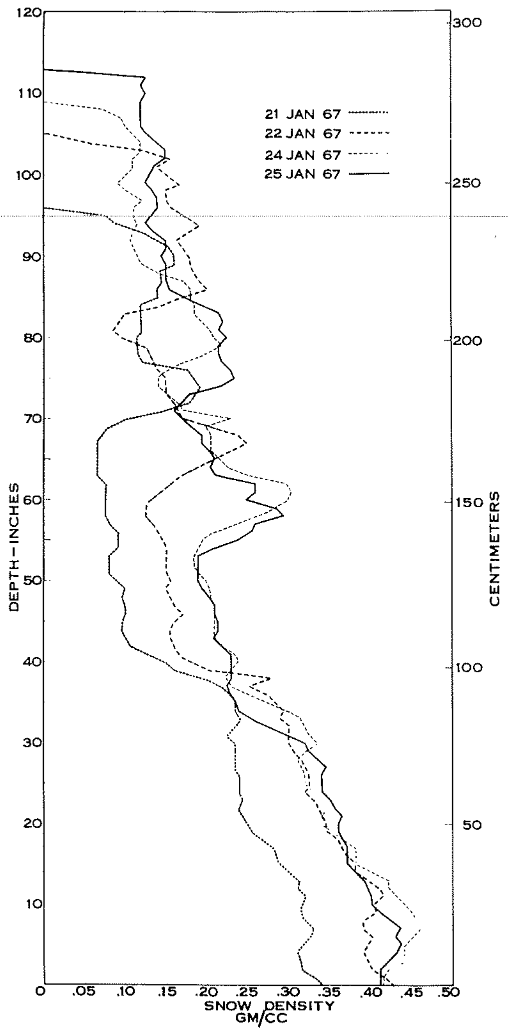


Figure 4. Light density layer extending from 40 to 67 in. above soil lost 7 in. depth to compression. Density increased from average of 7 percent to about 20 percent.

3. The amount of rainfall absorbed by a snowpack may be determined. On March 1, 1967, a study was initiated on a 71-in. (180.34 cm) snowpack containing 19.9 in. (50.55 cm) of water. A total of 10.56 in. (26.82 cm) of water was sprinkled onto the snowpack at the rate of 0.33 in. (0.838 cm) per hour. Profiles were obtained at regular intervals throughout the study period. The amount of water held in the pack and its location could be determined at any time. After drainage, the pack contained 28.8 in. (73.15 cm) of water, an increase of 8.9 in. (22.61 cm) (Fig. 5).

We believe that the amount of water retained by snow can be determined through research. We further believe that, if one knows the day-to-day history of a snowpack from study of daily profiles, he can determine the amount of new water that the pack will hold at any time. This information is vital to prediction of floods that are caused by rain falling on and melting snowpacks.

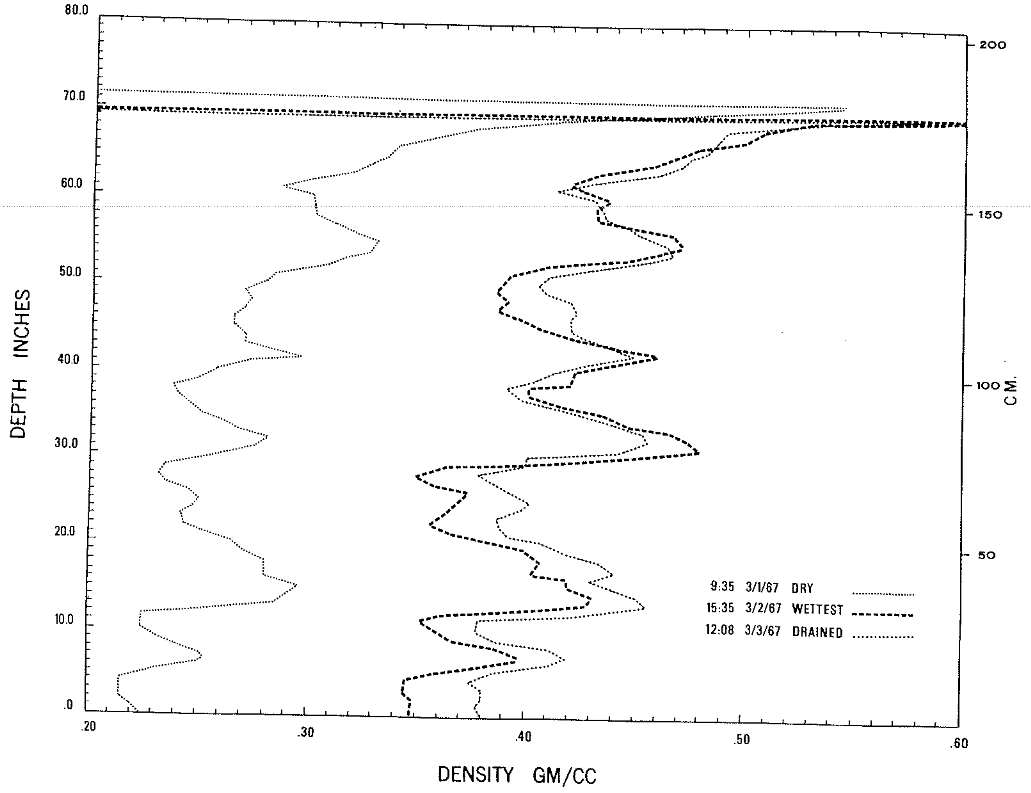


Figure 5. Density increased after water was applied to light density snowpack.

A natural rain on snow event occurred during the period January 17 to January 23, 1969. A 79-in. (200.66 cm) snowpack containing 29.95 in. (76.07 cm) of water received 12.30 in. (31.24 cm) of water as snow and rain. Of the total precipitation, 7 in. (17.78 cm) fell as rain or as snow of 30 percent density, which melted within a few hours.

The original pack had a uniform density ranging from 30 to 38 percent from ground line to 40 in. (101.6 cm) (Fig. 6). Densities from 40 in. (101.6 cm) to 79 in. (200.66 cm) decreased gradually to 15 percent near the snow-air interface. The snow in this pack had accumulated from frequent storms with no intervening melt and refreezing. Thus, no ice lenses were present. Free water content as determined by freezing calorimetry was 3 percent or less. The pack had densified by compression alone. It was in an ideal condition to hold more water. After the rain stopped, new snow increased pack depth to 100 in. (279.4 cm).

The 79-in. (200.66 cm) snowpack absorbed 6.44 in. (16.36 cm) of new water between January 18 and 21. Later it absorbed 0.56 in. (1.42 cm) of rain that fell mixed with the 27 in. (68.58 cm) of new snow on January 23. Another inch (2.54 cm) of rain was held in the new snow. The original pack increased in density by an average of 9 percent. Density increases for different snow layers ranged from 3 to 24 percent (0.03 to 0.24 g/cm^3) over those prevailing at the beginning of the storm. As a result of our studies we were able to predict prior to rainfall the amount of water this snowpack would hold.

POSSIBLE APPLICATION OF PROFILING SNOW GAGE DATA

With the availability of the profiling snow gage, snow scientists should be able to reexamine current theories in snow hydrology. Where these are deficient it may be

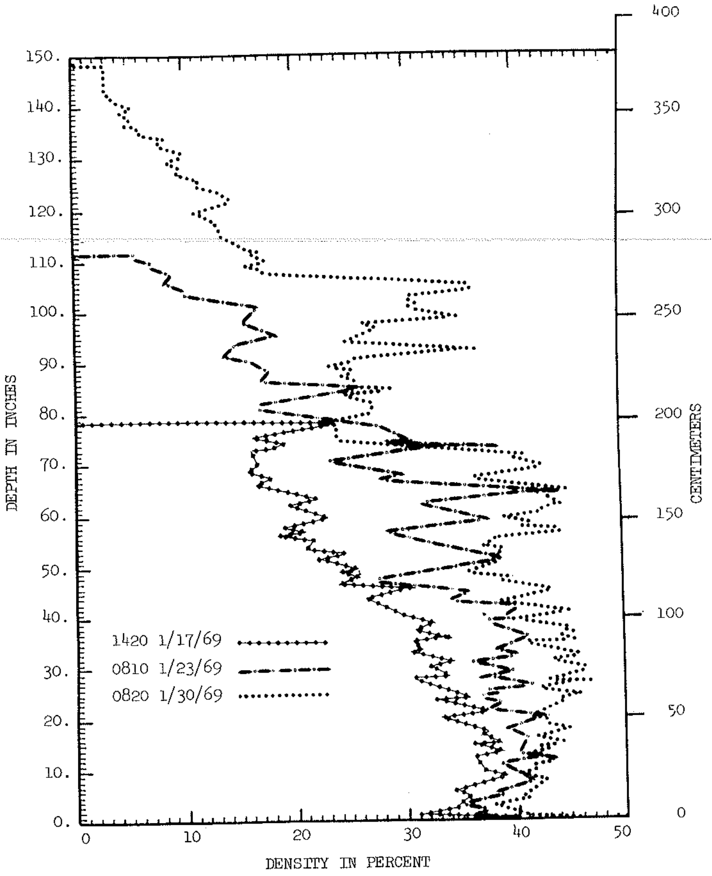


Figure 6. Snow profiles of snowpack at Central Sierra Snow Laboratory for storm of January 18-30, 1969.

possible to develop new theories from which more precise snowmelt equations can be formulated.

In operational snow hydrology, the use of data from the profiling snow gage opens a new dimension to streamflow forecasting. With the knowledge of the pack gained from study of profiles obtained throughout the accumulation and melt season, one should now be able to predict the reaction of the pack to meltwater or rainwater moving into the profile. Accurate predictions may be made of the effect of such events on water delivery from the snowpack and to streamflow increases.

More accurate streamflow predictions from snowmelt could result in better scheduling of reservoir operations and in less "reservoir spillage." In some flood situations such knowledge could conceivably save lives and property, including highway structures.

Avalanches are claiming a progressively greater toll of life and property as greater leisure time enables more people to participate in winter sports. Many ski resorts are situated in prime avalanche hazard areas. Most alpine roads pass under avalanche paths.

The causes of avalanches are still not fully understood. Basically, they are believed to be caused by movement of a snow overburden overlying a slippage plane in the snow. The reason for development of this slippage plane may be related to the development of depth hoar. We believe the development of this layer can be monitored with the snow gage because it normally consists of a change in density. Increase in weight of the snow above a slip plane can be caused by water absorption by the snow from rain falling on snowpacks. This increase in weight can be determined through monitoring of density.

With the discovery of oil in the Arctic has come an increased need for remote landing strips and roads. Some of these will probably be unattended for long periods of time. It should be possible to monitor snow strength and new snow depth on these improvements with the profiling gage.

The gage should fill a need for highway departments that must keep seldom used, remote mountain roads passable. With use of the telemetered snow gage data, highway personnel can determine whether snow or rain is falling, the amount of snow already on the ground, and its condition.

The current snow gage is an experimental model and requires an operator. Plans call for development and fabrication of a remotely operated, telemetered gage. We hope to have the first prototype gage installed before snow falls in the fall of 1970. Commercial gages should be available within another 1 to 2 years.

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Informal Discussion

L. G. Byrd

What is the nature of the system? Is it designed for permanent installation, or can it be moved as required?

Smith

We have both a portable system and a permanent installation. The package that is being prepared now is going to be modular, such that you could break it off at any point. It is a portable system that a man should be able to carry in a backpack on skis.

Ice Adhesion and Abhesion: A Survey

H. H. G. Jellinek

Understanding adhesion is essential for solving problems of ice adhering to aircraft, runways, ships, and all kinds of solid surfaces. These problems have not been solved satisfactorily in many cases; frequently mechanical devices rather than principles of interfacial physical chemistry have to be used for minimizing ice adhesion. This paper discusses some of the fundamental parameters in adhesion, recent work on ice adhesion, application of fundamental principles of interfacial physical chemistry, effects of mechanical, rheological, and morphological properties of ice and its substrates, transition layer in the ice-air or ice-solid interfaces, and significance of some recent developments in interfacial physical chemistry for the problem of ice adhesion.

Ice is one of the best adhesives in nature as people in cold regions are well aware. This property of solid water substance is of great fundamental interest for surface science and has been studied quite thoroughly under well-defined conditions in the laboratory. Many of the general fundamental principles connected with adhesive properties of materials on a macroscopic and molecular scale are apparent in the case of ice. However, there are also many abnormal features peculiar to this substance, which have to be considered in detail in order to understand ice adhesion fully.

The problems of ice adhesion—or ice abhesion, which is a more apt term in this connection—encountered in practice are quite different in nature from those studied in the laboratory. Still, the principles of ice adhesion can be discerned in many practical problems, although they are often nearly completely obscured and are not of main significance.

It is quite feasible to choose satisfactory substrates of sufficiently hydrophobic nature to diminish ice adhesion to an acceptable extent, but the main problem here is that such substrates become contaminated after a few abhesions and become useless. The same is true for special interfacial films (e.g., monolayers); these not only deteriorate but are removed on repeated abhesion. Thus, the problem here is to find not so much a suitable hydrophobic surface, which can be achieved fairly easily, but a surface that renews itself during use and that remains efficient. Thus icing of aircraft, ships, vehicles, instruments, and windows is the problem in ice adhesion or abhesion, and it is here that satisfactory long-lasting solutions have to be found.

Thus, there are 2 large areas in ice adhesion: the fundamental area, where the principles of surface science can be directly utilized to a large extent, and the practical area, which in the past was almost completely divorced from the fundamental aspects and which presents additional problems of a special type. Recently progress has been made by Zisman's discovery of the critical surface tension and by using lubricants and self-healing films, which may well further advance the solution of the practical ice abhesion problems (1, 2, 3).

A brief survey of fundamental aspects of ice adhesion and principles underlying the practice of ice abhesion is presented here. First, a short summary of general theoretical principles of adhesion is given to place ice adhesion in the general context of the field of adhesion.

SOME FUNDAMENTAL CONCEPTS

Thomas Young introduced the contact angle θ in 1805 (4, 5). Complete wetting of a surface takes place if $\theta = 0$ or $\cos \theta = 1$; a liquid cannot spread on a surface if $\theta > 0$.

The contact angle is always smaller than 180 deg; thus any liquid wets any solid to a certain extent. θ is independent of drop volume, if the surface is ideally smooth. θ is an inverse, while $\cos\theta$ is a direct measure of wettability (Fig. 1). Although there is not always a unique relation between adhesive strength and θ, it can serve as a useful guide in adhesion work. Surface roughness, r, can have an appreciable effect on the contact angle. The ratio of the geometrical area to the apparent area (i.e., envelope covering all peaks) is given by (6)

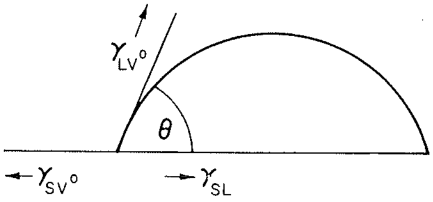


Figure 1. Contact angle between a liquid and a solid substrate (89).

$$r = \frac{\cos\theta'}{\cos\theta} \tag{1}$$

Here θ' is the contact angle of the rough surface. Equation 1 implies that for $\theta < 90$ deg, $\theta' < \theta$, and for $\theta > 90$ deg, $\theta' > \theta$ respectively.

The equilibrium for all surface tensions acting at a phase boundary of a drop is given by Young's equation

$$\gamma_{SV^\circ} - \gamma_{SL} = \gamma_{LV^\circ} \cos\theta \tag{2}$$

where the subscripts SV° and LV° refer to the solid and liquid tensions respectively in equilibrium with the vapor of the liquid; SL signifies the solid-liquid interfacial tension.

The reversible work of adhesion, W_A per unit surface area, is given for 2 liquids or 1 liquid and 1 solid respectively by (7)

$$W_A = \gamma_{S^\circ} + \gamma_{LV^\circ} - \gamma_{SL} \tag{3}$$

S° refers to the solid in vacuum. If, however, a monolayer of the liquid is left on the solid surface on removal of the liquid, the reversible work of adhesion W_A^* is

$$W_A^* = \gamma_{SV^\circ} + \gamma_{LV^\circ} - \gamma_{SL} \tag{4}$$

Hence, combination of Eqs. 2 and 4 gives,

$$W_A^* = \gamma_{LV^\circ} (1 + \cos\theta) \tag{5}$$

or

$$W_A = (\gamma_{S^\circ} - \gamma_{SV^\circ}) + \gamma_{LV^\circ} (1 + \cos\theta) \tag{6}$$

The first term in Eq. 6 can be written

$$f_{SV^\circ} = W_A - W_A^* \tag{7}$$

f_{SV° is always positive. In general

$$W_A > \gamma_{LV^\circ} (1 + \cos\theta) \tag{8}$$

or

$$W_A > W_A^* \tag{9}$$

If S, the initial spreading coefficient, is defined as

$$S = \gamma_{S^\circ} - \left(\gamma_{LV^\circ} + \gamma_{SL}\right) \tag{10}$$

then for organic liquids spreading on organic surfaces, γ_{SL} is negligible compared with γ_{LV°; hence,

$$S = \gamma_{S^\circ} - \gamma_{LV^\circ} \tag{10a}$$

For $S > 0$, spreading occurs; if $S < 0$, spreading is not possible. Zisman (1) identifies these as high and low energy surfaces respectively. The former are surfaces of solids having large specific free surface energies (>100 erg/cm^2, e.g., metals, metal oxides, nitrides, silica, and diamond; these range from 500 to 5,000 erg/cm^2). The latter belong to soft organic solids and most polymers (<100 erg/cm^2). Thus liquids with low energy surfaces can easily spread on solids with high energy surfaces.

Zisman found interesting and very important relationships for liquids of a homologous series (e.g., alkanes) on a particular solid (e.g., polytetrafluoroethylene or polyethylene). Cos θ is directly proportional to the surface free energies of the liquid

$$\cos\theta = a - b\,\gamma_{LV^\circ} \tag{11}$$

where a and b are constants characteristic of the system (e.g., alkane plus polymer). If $\cos\theta = 1$ or $\theta = 0$, then $\gamma_{LV^\circ} = \gamma_C$ and Eq. 11 becomes

$$\cos\theta = 1 + b\left(\gamma_C - \gamma_{LV^\circ}\right) \tag{12}$$

γ_C is the important term designated as critical surface tension (CST). Equation 12 shows that only liquids that have a free surface energy, $\gamma_{LV^\circ} < \gamma_C$, can spread on the respective solid. Equation 12 is of great significance for the selection of hydrophobic

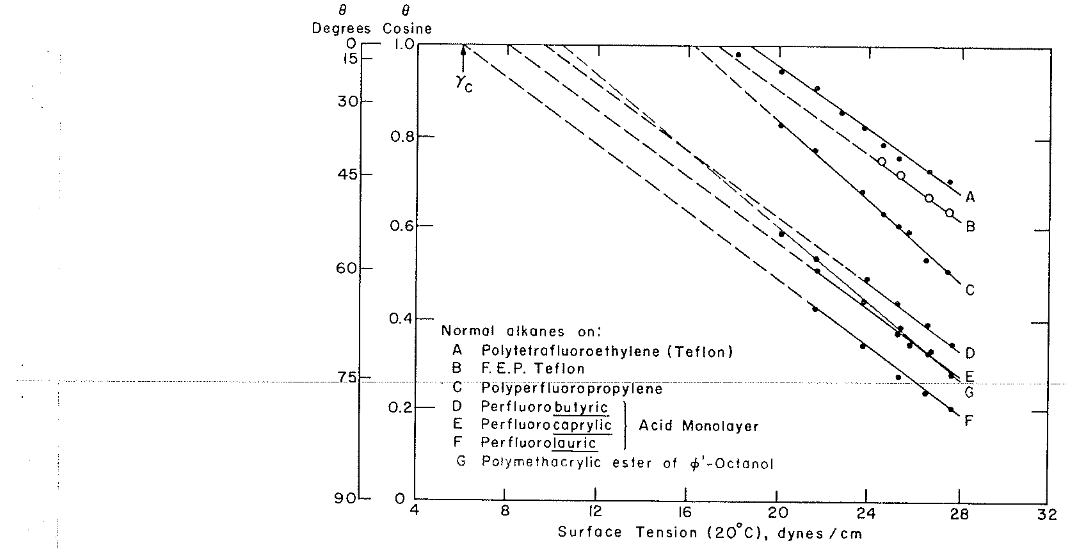


Figure 2. Contact angles formed by a series of n-alkanes on various fluorinated low energy solid surfaces (1).

surfaces. Water cannot spread on solid surfaces that have a γ_C value smaller than the surface tension of water. The lowest γ_C value known today is given by surfaces consisting of close packed $-CF_3$ groups (6 dyne/cm). A consequence of Eq. 12 is the following relationship:

$$W_A^* = \left(2 + b\,\gamma_C\right)\gamma_{LV^\circ} - b\,\gamma_{LV^\circ}^2 \tag{13}$$

Equation 13 represents the equation of a parabola and has been verified repeatedly (Fig. 2).

Some brief remarks may be made about the forces acting near an interface on an atomic or molecular scale. One has to deal with interfacial and cohesional forces and with materials under stress. There are quite a number of different adhesion theories based partly on the type of molecular or macroscopic forces involved; each has some justification under definite conditions. The mechanical theory ascribes adhesion to the flow of the adhesive into pores of the substrate, where solidification takes place. The adhesive is mechanically anchored to the substrate. The molecular aspect of the mechanical theory is in essence dealt with in the diffusion theory; polymer molecules diffuse to the interface and are absorbed. This theory is important for flexible linear polymers as adhesives, preferably mutually soluble. The chemical or molecular theory is important in dealing with forces at an interface. These forces can be of short- or long-range molecular interaction. Primary or short-range forces are due to highly directional covalent bonds (rupture energy 40 to 100 kg-cal/mole, e.g., diamond, crosslinked polymers). Another type of force is ionic (electrostatic force). This is less directional than the covalent bond. Metallic bonds are due to nonlocalized mobile electons; these bonds are of similar strength as covalent bonds. Image forces are produced in metals when a permanent dipole approaches. Hydrogen bonds are important in many cases. They are of longer range than most polar forces or van der Waals forces (dispersion forces about 10 kg-cal/mole). Permanent dipoles are somewhat stronger than van der Waals (dispersion) forces. Oriented dipoles exert an influence over many atomic layers. The secondary or van der Waals forces are very important and always present; they are also referred to as dispersion forces and are due to temporary dipoles of relatively short range (about 3 Å) and of 2 to 4 kg-cal/mole strength. They account for 75 to 100 percent of molecular cohesion in most cases. The magnitude of these forces is proportional to the number of electrons in a chemical group. Thus, the dispersion forces are all similar for the following chemical groups: NH_3, OH, $-CH$, $-NH$, $-O-$, and $-CH_3$. These forces decrease with the sixth power of the distance. The interaction of different groups 1 and 2 is given by the geometric mean between 1 and 1 and 2 and 2; i.e.,

$$D_{12} \sim \sqrt{D_{11}\,D_{22}} \tag{14}$$

Fowkes developed a theoretical approach to the problem of surface energies of solids (8, 9, 10, 11, 12). It was assumed that the contribution of dispersion forces to free surface energies is additive. The attraction between 2 unlike compounds per unit area is given by $(\gamma_1^d\ \gamma_2^d)^{1/2}$, where d indicates the contribution of dispersion forces. Hence, if these forces contribute the major part to interfacial free energy, a relationship should hold as follows:

$$\gamma_{12} - \gamma_1 - \gamma_2 = -2\left(\gamma_1^d\ \gamma_2^d\right)^{1/2} \tag{15}$$

This equation is obeyed quite frequently, especially if one of the compounds is nonpolar or nonhydrogen bonding. In this context, it means that in such a case only dispersion forces are operative. For example, only dispersion forces are assumed to be operative in the paraffin-water system; γ_{12}, γ_1, and γ_2 are known for this system. Hence, one has, according to Young's equation (here $\gamma_S = \gamma_1$, $\gamma_L = \gamma_2$, and $\gamma_L > \gamma_S$),

$$\gamma_L (1 + \cos\theta) = 2\left(\gamma_L^d \gamma_S^d\right)^{1/2} \tag{16}$$

or

$$\cos\theta = 2\left(\gamma_S^d\right)^{1/2} \frac{\left(\gamma_L^d\right)^{1/2}}{\gamma_L} - 1$$

Cos θ plotted versus $\left(\gamma_L^d\right)^{1/2}/\gamma_L$ for a series of nonpolar liquids gives γ_S^d by extrapolation to $\theta = 0$. The slope of the straight line is $2\left(\gamma_S^d\right)^{1/2}$ and its origin $\cos\theta = -1$. This is somewhat similar to Zisman's γ_C (CST), if only dispersion forces are involved. (γ_C: F < H < Cl < O < N.)

Fowkes (8, 9) refined this treatment recently as far as the summation of the forces is concerned. This summation was carried out in the past according to Polanyi and London (13). Their treatment caused quite a substantial error in the result. Crowell (14) used a model in which the dispersion energy involving molecules is "smeared out" uniformly over planes parallel to the surface. The calculation is relatively simple and yields more accurate results.

ICE ADHESION (FUNDAMENTAL STUDIES)

Fundamental investigations concerning ice adhesion are not too numerous, although some of them are very detailed. The theoretical principles of adhesion are often obscured by imperfections in the ice, which decrease the theoretically expected tensile and adhesive strengths. However, this is a general phenomenon of materials; their experimental strength is only a small percentage of that theoretically possible. Forces in the interface on a molecular scale not only play a role in general adhesion and in particular ice adhesion but also are often overshadowed by the plastic-elastic and thermal properties of ice and those of the substrate. Severe stress concentrations can be set up partly conditioned by the geometry of a particular joint; adsorption of gases can interfere. Thermal expansion coefficients and thermal conductance of the materials are also of significance.

Thus adhesion, and in particular adhesion of ice, deals with a very complex situation, which frequently makes it quite difficult to recognize the underlying fundamental principles. In particular ice, as will be seen later, has very peculiar interfacial properties, which influence its adhesive behavior and make its interfacial properties of special importance to surface science. A number of workers have attempted to investigate the adhesive properties of ice from a fundamental point of view by systematically collecting experimental data under rigidly standardized conditions and attempting to interpret them with the help of known principles or by developing new hypotheses and theories. The types of experiments usually performed are tensile and shear tests; the latter are sometimes performed by applying a torque. The conditions are systematically altered, as will become apparent later, in the hope of ascertaining generally valid relationships. Working with ice presents quite formidable experimental problems, and establishing really satisfactory techniques is not an easy task. Strength measurements have always to be performed in large numbers. The results are statistical in nature and have to be evaluated on this basis. Thus, all final results are average values of a more or less wide distribution of individual values. In comparing work of various authors, one has to carefully ascertain the degree to which such results have been obtained by comparable experimental methods and what their limits of error are. Even slight variations in the preparation of ice may produce marked differences in experimental results (e.g., the presence of gas or air in ice is very significant, and the technique of preparing an adhesive joint is important for whether the air is driven away from the interface or not). It is quite surprising that various workers nevertheless obtain experimental results that show similar regularities.

The most important and extensive work is contained in publications by Berghausen et al. (15, 16, 17, 18), Bascom et al. (19), Ford and Nichols (22, 23), Jellinek, (24, 25, 26), Landy and Freiberger (27, 28), and Raraty and Tabor (29, 30), and, to a lesser extent, Sellario (31), Loughborough (32), Brunner (33), and Hunsacker et al. (34). Only Berghausen et al. and Jellinek among these authors performed tensile experiments, whereas the others carried out shear (or torque) tests only.

Tensile Experiments

For details of apparatus, reference should be made to the original papers. Berghausen et al. constructed a very elaborate tensile strength apparatus, where ice could be sandwiched between metal cylinders, which formed the substrate. These metal pieces could be directly refrigerated in situ, and the gap width could be adjusted from about 5×10^{-3} cm to larger widths. Water was double distilled and had a specific conductivity of not more than 2×10^{-6} mhos. The lowest temperature that could be reached with this apparatus was -35 C, and the rate of freezing could be varied. Usually the water was saturated with air or helium, but freezing was so arranged that gas was driven away from the interface and accumulated as bubbles in the middle of the ice specimen. The rate of force application could also be varied from 1.4 to 22.7 kg/sec. The technique was rigidly standardized. Berghausen's most important results from tensile tests are as follows:

1. Only cohesive breaks were observed at all gap widths with metals as substrates. Ice prepared from helium-saturated water showed smoother breaks than ice prepared from air-saturated water. Helium-saturated ice showed tensile strength (35 kg/cm^2) higher than that of air-saturated ice (stainless steel-ice); it was independent of gap width and temperature (-5 to -15 C, area 7 to 2 cm^2, and gap width 5×10^{-3} cm to 4.5×10^{-2} cm). With aluminum as substrate, the cohesive strength was again larger in the case of the helium-saturated ice, but here the slopes of the strength versus gap width plot have different values in each case, indicating a common or crossover point near very small gap width for the helium and aerated ice.
2. The tensile strength increases with decreasing ice volume; this is a phenomenon common to all ordinary materials (this was also found for ice by Jellinek, as discussed later). The curve obtained indicates that it may go through a maximum at very small gap widths (volumes); the subsequent decrease in strength at still smaller widths may be due to unfrozen water and to radial stresses in the sandwiched ice. Air bubbles may also be responsible for this maximum. At -15 C, the tensile strength found was 91.4 kg/cm^2 for a volume of 3.26×10^{-3} cm^3, and 21.1 kg/cm^2 for a volume of 6.52×10^{-2} cm^3.
3. Ice in small gap widths indicated a negative temperature coefficient, whereas the trend was in the opposite direction for larger widths.
4. According to these authors, the differences in strength found for aluminum, mild steel, and stainless steel substrates are not due to the different elastic properties of these metals but rather to their different thermal properties. There is always an oxide film on aluminum, which is a good heat insulator; mild steel tends to rust, and this also provides thermal insulation. On the other hand, stainless steel is a good heat conductor. Thus the rate of freezing will differ for each of these metals. It was also observed that, for a given frozen ice volume, the tensile strength increases with decreasing diameters (i.e., with larger gap width). This increase is believed to be due to the slower overall rate of cooling of the wider gaps.
5. Metals covered by monolayers of stearic and perfluorodecanoic acid (hydrophobic surfaces) still gave cohesive breaks. However, when thicker layers were deposited on the substrate surfaces, failure occurred, for instance, in the stearic acid layer. Thus, the cohesive break shifted to the mechanically weaker material. Abhesions were repeated about 12 times by using the same coating. The strength of the first break amounted to 1.9 kg/cm^2 and of the eleventh break, to 35.2 kg/cm^2; obviously, the layer was progressively removed by repeated abhesions of the ice (-16 C, gap width 2.54×10^{-2} cm).
6. Tests were also performed with low density polyethylene (2.54×10^{-2} cm in height) having smooth surfaces. The polymer was especially fixed by suitable chemicals to the aluminum substrate. The ice was helium saturated. Adhesive breaks were observed; whether a monolayer was removed with the ice—a cohesive break taking

place—was not investigated. This is true for most investigations. Though adhesive breaks are referred to here, breaks are meant that may have removed a monolayer of one or the other component. Strictly speaking such breaks are also cohesive. At a gap width of 46.23×10^{-3} cm and at -15 C, the adhesive strength found was 21.82 kg/cm^2; on extrapolation of the strength values to zero gap, it increased to 44.65 kg/cm^2. This increase may actually indicate that cohesive breaks are still involved rather than adhesive ones. For a slight increase in diameter (from a diameter of 0.95 cm to one of 1.27 cm), a mixture of adhesive and cohesive breaks is obtained. The tendency for cohesive breaks actually increases for small gap widths.

Jellinek had not so elaborate an arrangement as Berghausen, but conditions could be exactly reproduced and the rate of load application could be varied. The lowest temperature that could be reached was about -45 C. Highly polished stainless steel disks were used. Double distilled water was passed through exchange resin and continuously boiled to remove air. Mounting was rigidly standardized and was performed so that any residual air was driven away from interfaces. Thick layers of ice were prepared with snow-ice. Gap widths were measured with a Starrett gage to 2.5×10^{-4} cm. Tensile strength was measured with a 500 lb Baldwin cell, and the output was traced on a recorder. All breaks were cohesional (though some breaks left part of the substrate surface bare). Most took place near one of the interfaces at an angle of about 20 deg. These breaks were quite jagged. Less frequently, smooth breaks occurred at right angles to the interface. The experimental results can be summarized as follows:

1. Tensile strength increases linearly with stress rate, passes through a maximum, and comes to a plateau corresponding to the bulk tensile strength of ice ($\epsilon \cong 15.8$ kg/cm^2). Typical values are given in Table 1. At least 12 tests were carried out at each rate.

$$\bar{S} = C\left[\left(\frac{v\epsilon}{\epsilon v_m - 1}\right) e^{-\epsilon v} + 1\right] \tag{17}$$

where ϵ is the inverse stress rate, C is a constant, and v_m is the rate of loading at maximum tensile strength. All subsequent experiments were carried out in a range where tensile strength is independent of stress rates and areas (Fig. 3).

2. Similarly, as was found by Berghausen et al., the tensile strength increases rapidly with decreasing ice volume. However, each cross-sectional area gives a separate curve. Logarithmic plots of tensile strength versus volume give parallel straight lines. A single straight line is obtained, including all areas, by plotting log $[(\bar{S} - C)/A]$ versus log V over a thousandfold range of volumes. C is a constant, $\bar{S}$ the tensile strength, and A and V area and volume respectively. In the specific case investigated here, the relationship is (Fig. 4)

$$\bar{S} = \left(2.74AV^{-0.84} + 9.4\right) \tag{18}$$

TABLE 1

TENSILE STRENGTH AS FUNCTION OF STRESS RATE—-4.5 C, AREA 3.14 cm^2, AND HEIGHT 2 cm

Stress Rate, v (kg-cm^2/sec)	Mean Strength, S (kg/cm^2)	Standard Deviation (±kg/cm^2)	Standard Error of Mean (±kg/cm^2)
0.051	14.7	2.6	0.7
0.110	16.7	2.5	0.7
0.210	17.0	3.9	1.2
0.570	15.6	2.2	0.6
1.100	16.1	2.1	0.8

3. The theoretical tensile strength value of ice is given by

$$\bar{S} = \frac{2\gamma_i}{d} \tag{19}$$

Here γ_i is the surface free energy of ice, recently determined by Hobbs (35) as $\gamma_i = 109$ erg/cm^2. If d is taken as 2×10^{-8} cm, a value of $\bar{S} = 10{,}900$ kg/cm^2 results. The actual tensile strength of ice is only a small fraction of this value (15.8 kg/cm^2). Czysak (36) calculated the cohesive strength of ice by classical and quantum

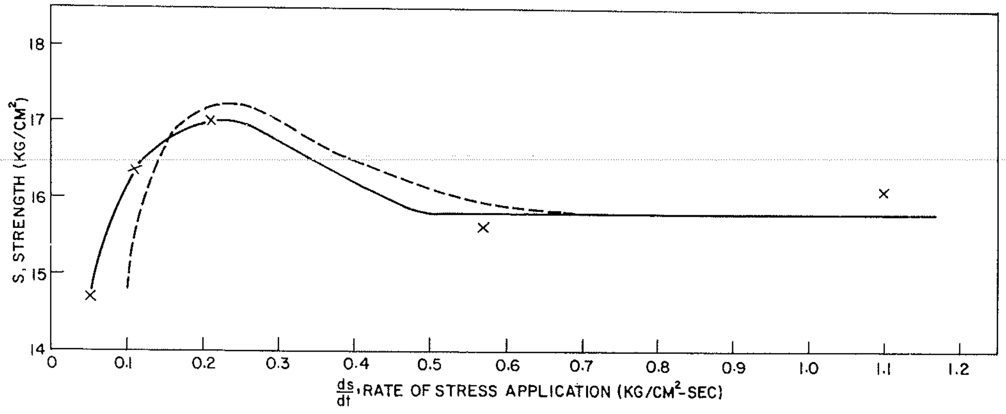


Figure 3. Average tensile strength as a function of rate of stress application for snow-ice cylinders 2 cm in height and 2 cm in diameter (5). Dotted line calculated according to Eq. 17.

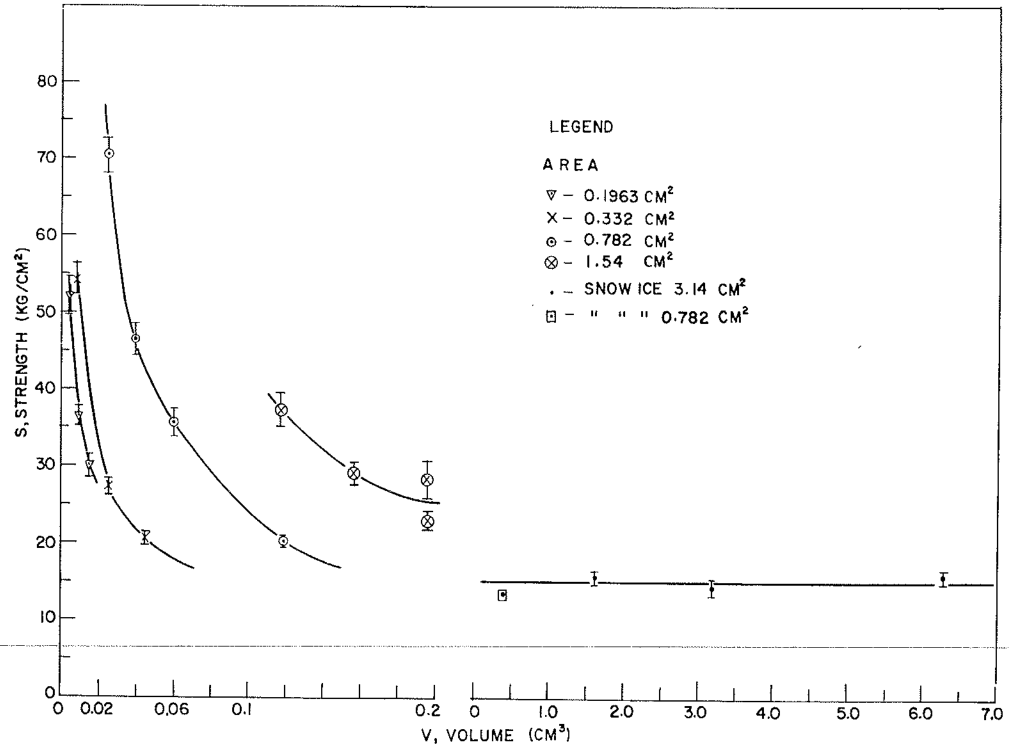


Figure 4. Average tensile strength as a function of ice volume (5, Fig. 7). Each point represents average value of at least 12 tests, and ranges indicated are standard errors of the mean.

mechanical methods, and obtained 6,770 and 13,050 kg/cm^2 respectively. This discrepancy of experimental and theoretical strength is usually ascribed to imperfections in the substance under consideration and is a general phenomenon. The probability of finding an imperfection decreases with the volume of the substance under test. Jellinek succeeded in deriving this increase with decreasing volume on a statistical basis, obtaining an expression in agreement with experimental data.

$$\bar{S} = k A^{1/\beta} V^{-1/\beta} + C \tag{20}$$

Here k, C, and β are constants; A and V are the cross-sectional area and volume of ice respectively. Equation 20 fits the experimental data except for a small discrepancy believed to be due to stress concentrations influencing the purely statistical aspect of the derivation.

4. There is an indication that tensile strength decreases slightly with decreasing temperature (-11 to -45 C).

5. Experiments with polystyrene and polymethylmethacrylate as substrates were also performed. These polymers were cast sheets and had very smooth surfaces. Mainly adhesive breaks were obtained. The adhesive stress for polystyrene-ice as a function of temperature gave a straight line to -25 C (this was the lowest temperature investigated; the area was 1.54 cm^2 and the height 0.1 cm). This line is given by

$$\bar{S}_A = -0.173\, t^{o} + 1.81 \tag{21}$$

6. Cross section and rate of stress application in the range investigated have no effect. A mean adhesive strength of 4.4 kg/cm^2 (standard deviation ±2.9 kg/cm^2 and standard error of mean ±0.7 kg/cm^2) was obtained for the polymethylmethacrylate-ice system (cross-sectional area 0.785 cm^2, height 0.1 cm, temperature -5 C); 19 adhesive breaks and 4 border-line cases were observed. The adhesive strength for this system is larger than for the polystyrene-ice system. This is understandable because polymethylmethacrylate is a polar compound, whereas polystyrene has only a very small dipole moment. The surfaces of these polymers become cloudy and crazed after 3 tests, and test pieces have to be renewed. Whether a real adhesive break takes place or whether a polymer monolayer or a very thin layer is removed is not known.

In summary, it can be stated that similar relationships, not numerical but in type, are found in the studies of both Berghausen et al. and Jellinek. The increase in tensile strength with decrease in volume is similar in both cases, and so is the area relationship. Only cohesive breaks were found in both studies with metal substrates, whereas polymer layers thicker than a monolayer gave predominantly adhesive breaks. The temperature coefficient with metals as substrate (cohesive breaks) showed a negative trend in both cases. The tensile and adhesive strength values were only small fractions of the corresponding theoretical values, indicating the presence of imperfections in ice.

Shear Tests

Shear tests were carried out by several workers: Bascom et al. (19), Ford and Nichols (22, 23), Loughborough (32), Brunner (33), and Hunsacker et al. (34). Shear apparatus was used in which, in principle, a prism of ice is sheared off a flat surface, the force acting in the ice-substrate interface. Some workers used torque devices such as napkin joints and also centrifugal methods. Some of the results of these workers are considered and compared.

Table 2 gives some comparable test results obtained by Sellario (31) using the torque method and Loughborough using the centrifugal method. Sellario's method gives higher adhesive values than Loughborough's centrifugal apparatus.

Table 3 gives a summary of some of the results of some experiments performed by Brunner.

TABLE 2

ABSOLUTE AND RELATIVE SHEAR STRENGTH OF METAL-ICE INTERFACES

Metal or Ice	Loughborough		Sellario	
	kg/cm^2	Relative Values[a]	kg/cm^2	Relative Values[a]
Copper	8.72	1.0	22.36	1.0
Steel(iron)	13.01	1.5	26.58	1.2
Aluminum	15.47	1.8	24.68	1.1
Ice (cohesion)	17.58	2.0		

[a]Relative values are referred to ice-copper adhesive strength taken as one.

TABLE 3

RESULTS OF EXPERIMENTS BY BRUNNER

Substrate	Percentage of Total Which Gave Adhesive Breaks	Adhesive Strength[a] (kg/cm^2)
Metal	17	9.5
Oxidized metal	39	8.8
Metal as obtained from factory	37	7.2
Ski-lacquer	35	6.3
Mainly consisting of polystyrene	39	5.9
Paraffin	50	4.6
Silicone grease	79	3.1

[a]Includes breaks leaving four-fifths of surface bare.

Raraty and Tabor (29) employed torque, studying the effect of various substrates on adhesive strength. Ice annulus and cylinders were investigated. A paper by Bowden and Tabor (30) is of interest in this connection.

1. The experiments indicated that creep of ice takes places. This creep remained small until a critical torque was reached; the torque was applied in small increments. The primary cause determining failure is strain rate at the interface and not the magnitude of strain. In all subsequent experiments, torque was applied in increments and adhesive strength in kg/cm^2 was expressed as the torque at failure divided by the area of ice-solid interface being sheared. Air bubbles were formed relatively far away from the interface.
2. Rate of freezing did not affect the adhesive strength, which increased with decreasing height of the cylindrical specimens. This is similar to the observations made on cohesive breaks (tensile).
3. The adhesive strength for cylindrical and annulus specimens decreases linearly with decreasing temperature down to -25 C for cylinders; however, the strength values become constant below about -7 C for annulus specimens and only cohesive breaks take place. Similar results are obtained for ice in the form of an annulus as for complete napkin ring joints. The fracture plane lies at 45 deg to the interface. Above -7 C, the break is ductile and adhesive, and creep and yielding take place in or near the interface. These authors try to explain the tests on the basis of creep as determined by Glen (37) or Jellinek and Brill (38); the agreement is only approximate.
4. The adhesive fracture range for the annulus specimens is appreciably extended to lower temperatures for contaminated surfaces (e.g., stearic acid monolayer, silvered surface, and the like); the slope of the straight line parts increases, but otherwise the type of relationship is preserved for the various covered surfaces.
5. Aluminum gave only cohesive breaks.
6. The range of adhesive fractures is extended for polymers as substrates to about -10 C.
7. Addition of salts decreases the mechanical strength of ice and increases its creep rate.

Ford and Nichols (22, 23) carried out well-controlled shear experiments, most of them at -6 C. The rate of loading was approximately 1.41 $kg\text{-}cm^2/sec$. Brass and stainless steel were electrolytically polished. Water was triple distilled and boiled before being applied to the substrate. This procedure was used for thin ice specimens. Bulk shear strength was measured differently; details are given in their paper.

1. Bulk experiments were carried out over a temperature range of -2 to -21 C. The corresponding average shear strengths range from 25.3 to 31.5 kg/cm^2. There is a slight trend to higher values with decrease in temperature.
2. Cohesional breaks (average strength 43.7 kg/cm^2) were obtained with ice-stainless steel (ice height 1.27 cm, -6 C); mixed cohesional-adhesional break (strength

76.6 kg/cm^2) occurred with an ice height of 0.1 cm. Apparently the average strength value increases with decreasing height of the ice specimen. Brass, aluminum, and Teflon with ice of 0.1 cm height also gave mixed cohesional-adhesional breaks at -6 C. The strengths were 88.6 and 47.1 kg/cm^2 respectively. The values agree closely with those of Freiberger and Lacks (39).

3. Lubricated surfaces scarcely show a difference in type of break and magnitude of strength on repeated abhesions from those given by bare surfaces; however, if surface active agents are added, adhesional breaks are obtained. In the case of Teflon it is not necessary to have additives; lubrication is sufficient to obtain adhesional breaks only.

The second part of Ford and Nichols' paper deals with adhesion of ice to bulk polymers, polymer films, lubricated polymers, and lubricated metals at 3 temperatures.

4. Adhesive strength was measured with bare nylon, polyethylene, and Teflon surfaces, and surfaces covered with silicone grease at -1 C. The adhesive strength dropped from a finite value to practically zero, although in the case of Teflon its unlubricated surface already showed zero strength. At -6 C, the drop in strength is very dramatic on lubrication with silicone and petroleum grease (this latter grease contained lithium stearate, basic barium dinonylnaphthalene sulfonate, and 1-phenylnaphthylamine). At -20 C the results are similar; the adhesive strength of the uncovered polymer surface scarcely changes with temperature.

5. Unlubricated polymer films on metal substrates behave differently at -20 C; here the adhesive strength remains finite (about 1.4 to 2.8 kg/cm^2).

6. The adhesive strength increases dramatically with the number of abhesions performed with the lubricated bulk polymer. The ease of increase of strength depends on the lubricant; silicone grease (J941-C-5000) lasts many more cycles than other lubricants. The increasing values tend eventually to those of the uncovered polymer, which is independent of the number of abhesions as long as the surface is kept clean (-20 C).

7. Lubricated metal surfaces initially show low adhesive strengths, but not zero (about 0.5 to 1.6 kg/cm^2) as is the case with polymers. Here, loss of effectiveness is also observed with repeated abhesions.

Landy and Freiberger (27) studied the adhesion of ice to polymers by carefully performing shear tests. All measurements were carried out at -12.2 ±1 C.

1. All adhesive tests with Teflon showed a strength of about 17.6 kg/cm^2 even after repeated abhesions. These were the lowest values found for polymers. Polymethylmethacrylate showed the highest value (87.9 kg/cm^2), this value remaining the same after 10 abhesions. The authors could not discover any correlation of the strength values of all the numerous polymers investigated with Zisman's critical surface tension (CST), γ_C, with contact angles, thermal conductivity, thermal expansion, porosity, and dielectric constant. They found some correlation with flexibility of the substrate. However, the extent of correlation is not sufficient to explain the behavior of the polymers completely. There are one or two additional factors of importance in this connection. If polymers of the same thickness having the same type of chemical bonding are grouped together, then it was observed that the ice adhesion in each group increases with the flexural modulus of the polymers. Hence for each such group, the mechanical deformation theory is followed quite satisfactorily.

2. The adhesive strength increased with thickness.

3. The results do not agree well with those of Ford and Nichols (22, 23). This may be due to the history of the polymers and to adhesion technique. Age of the ice-substrate bond also affects the strength somewhat.

4. Ice adhesion was also measured on ice-polymer systems immersed in water. In some cases, the adhesive strength passed through a maximum with time, in others the reverse took place.

5. It was expected that the adhesive strength would increase by decreasing the flexibility of the polymer. Preliminary experiments showed that addition of fillers and pigments, which decrease the flexural modulus, actually showed higher adhesive strength. Plasticizer may show the opposite effect. This has not yet been studied.

Bascom, Cottington, and Singleterry (19) also studied adhesion by shear. The influence of hydrophobic and hydrophilic surfaces was investigated. Permanent records of the rupture surfaces were obtained by making replicas. Contact angles were measured by the sessile drop method at 25 C. Shear strengths were measured at -6 C in the same apparatus as that previously used by Ford and Nichols. Ice was made in Teflon-coated foil molds. The water was redistilled from a quartz still. Air was removed by boiling (conductivity 1×10^{-6} $\text{ohm}^{-1}\ \text{cm}^{-1}$). The adhesive strengths of highly polished steel and steel covered by monolayers were compared. The ice was allowed to recrystallize overnight before the test was started. Results are given in Table 4. The hydrophobic monolayers decrease the adhesive strengths.

TABLE 4

CONTACT ANGLE AND SHEAR STRENGTH OF POLISHED AND COVERED STEEL

Surface	Contact Angle With H_2O	Shear Strength (kg/cm^2)	Type of Break
Steel	0	94.9	Cohesive-adhesive
Steel plus			
Octadecylamine	104	49.9	Adhesive
Stearic acid	104	61.2	Adhesive
Perfluorodecanoic acid	97	69.6	Adhesive
Polymethylsiloxane	103	69.6	Adhesive

6. Emery-abraded surfaces showed increased adhesive strength. The failure was always cohesive whether the metal was bare or covered by a monolayer.
7. Polymer coatings decrease the adhesive strength except for some of the siloxanes. Thick layers are more effective than monolayers.
8. The authors could not find a clear correlation between contact angle and adhesive strength.
9. Replicas were made of sheared surfaces and examined microscopically. Imposition of a hydrophobic monolayer between steel and ice reduced adhesive strength by about 30 percent and changed the break from cohesional to adhesional. The work of adhesion of water to a monolayer is low (the contact angle is high), but apparently this is not enough to actually give a low adhesive strength. Crystal defects seem to be present in greater concentration at an ice-monolayer interface than at an ice-hydrophilic steel interface.
10. Polymers tend to fail cohesively very near the interface as indicated by replicas; apparently relaxation is not fast enough. The macroscopic break "appears" to be adhesional. It is important to note that the rate of stress application in this work was 1.4 $\text{kg-cm}^2/\text{sec}$, whereas Jellinek used 0.7 $\text{kg-cm}^2/\text{sec}$.
11. Generally the impression was gained from replicas that adhesional breaks occur very near the interface in the case of polymer coatings and monolayers. Thus it appears that these adhesional breaks are rather cohesional breaks taking place in the substance of weaker mechanical strength (monolayer, polymer). This was assumed generally to be the case by Bikerman (40). Actually evidence was found of polymer fragments adhering to ice after rupture. The authors point out that with smaller stress application, the ice has sufficient time to relax by dislocation slip and various mechanical processes on a microscale; however, when force is applied very rapidly, there is not sufficient time for relaxation to occur before rupture.
12. Thin layers of water freezing on steel were investigated with polarized light during their formation. Initially, large crystals were formed that subsequently recrystallized into smaller polygonal grains. The authors assume that a similar process takes place during the formation of ice test blocks. However, recent experience shows that in ice, usually, small grains are first formed that then grow into larger ones (41). The authors assume further that the recrystallization and polygonization process creates a high density of dislocations at ice surfaces. The driving force for this dislocation movement to the surfaces or interfaces is, according to these authors, due to stress produced by the difference in thermal coefficients of expansion between ice and substrate. Thus adhesional failure is explained by high dislocation density in the interface, which leads to easy deformation by prismatic slip parallel to the interface.

Jellinek (24, 25, 26) also performed accurately controlled shear experiments. The water was treated as indicated before.

TABLE 5

ADHESIVE SHEAR STRENGTH OF SNOW-ICE AT -5 C AS FUNCTION OF CROSS-SECTIONAL AREA

Area (cm^2)	Adhesive Strength (kg/cm^2)	Standard Deviation ($\pm kg/cm^2$)	Time of Load Application (sec)
1.54	5.44	0.40	14
3.14	5.50	0.72	23
4.91	5.32	1.14	28
6.61	5.41	0.49	41

Note: All breaks adhesive; thickness of ice 0.2 to 0.4 cm.

1. First, snow-ice, sandwiched between polished stainless steel plates, was investigated at -5 C as a function of cross-sectional area. Results are given in Table 5.

2. Adhesive strength (stainless steel/snow-ice) as a function of temperature at constant height of ice (0.2 to 0.4 cm) and constant cross-sectional area can be expressed by a straight line until -13 C is reached where a sudden kink occurs and the adhesive breaks go over into cohesive breaks. The cohesive breaks are only very slightly dependent on temperature, decreasing slightly with decreasing temperature. The adhesive breaks as a function of temperature can be expressed by

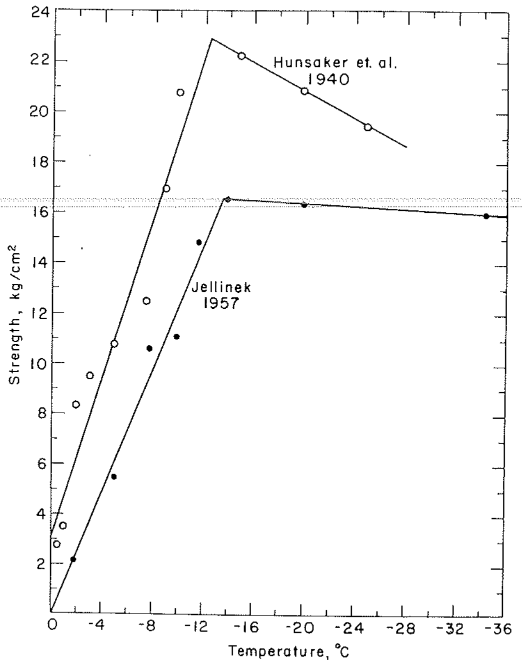


Figure 5. Strength as a function of temperature for snow-ice/steel and ice-brass obtained by shear for cross-sectional area 1.54 cm^2 and 0.2 to 0.4 cm in height. Adhesive breaks only down to -13 C, and cohesive breaks only below -13 C.

$$\bar{S}_A = 1.24\ t^o - 0.18 \qquad (22)$$

The magnitudes of strengths of the cohesive breaks obtained by shear tests are similar to those produced by tensile experiments. Also the type of break is similar (height 0.2 to 0.4 cm, area 1.52 cm^2). Hunsacker et al. (34), using brass-ice napkin joints, also found a similar trend in their shear experiments. Adhesive breaks occurred until -13 C was reached; at this temperature the breaks become cohesional and less dependent on temperature (Fig. 5).

3. Shear tests were also performed with ice frozen to smooth polystyrene. The rates of stress application for these experiments were from 0.3 to 1.0 kg-cm^2/sec.; these rates had no influence on the results. All breaks were adhesive.

4. The temperature relationship of the adhesive strength (0 to -16 C, area 9.61 cm^2, height 7.6×10^{-2} cm) for ice-polystyrene is given by

$$\bar{S}_A = 2.8 \times 10^{-2}\ t^o \qquad (23)$$

The rate of stress application was practically constant. Further work is described in a second paper (42) in which the shear apparatus was modified. The rate of stress application could be varied over large ranges.

5. Surface roughness had an appreciable effect on adhesive strength (Table 6). The average rate of linear travel up to maximum strength was 5.9×10^{-3} cm/sec while the average rate of stress application was 0.27 kg-cm^2/sec (stainless steel -4.5 C, height of snow-ice 0.1 to 0.2 cm, density 0.888 g/cm^3). Profilometer readings showed unevenness of 1.3×10^{-2} cm to 7.2×10^{-2} cm.

TABLE 6

SURFACE ROUGHNESS OF SUBSTRATE AND ADHESIVE STRENGTH, -4.5 C

Surface	Avg. Rate of Travel to Max. Strength (cm/sec)	Avg. Rate of Stress Application (kg-cm^2/sec)	Mean Adhesive Strength, 12 Tests (kg/cm^2)	Standard Deviation (±kg/cm^2)
Rough plates	5.9×10^{-3}	0.27	6.1	1.46
Polished, mat finish	5.4×10^{-3}	0.16	2.7	0.37
Bright mirror finish	5.8×10^{-3}	0.12	0.6	0.24

6. The stress versus time curves differ for the various degrees of roughness (Fig. 6). The rough surface shows a linear increase of stress with time up to a maximum value of 6.1 kg/cm^2, when the ice is suddenly released and the stress decreases very rapidly to zero. The mat finish only rises somewhat more slowly than in the previous case to a maximum of 2.7 kg/cm^2, when it drops very fast to zero. The mirror polish rises still more slowly to 0.45 kg/cm^2, or in another experiment to the same value with

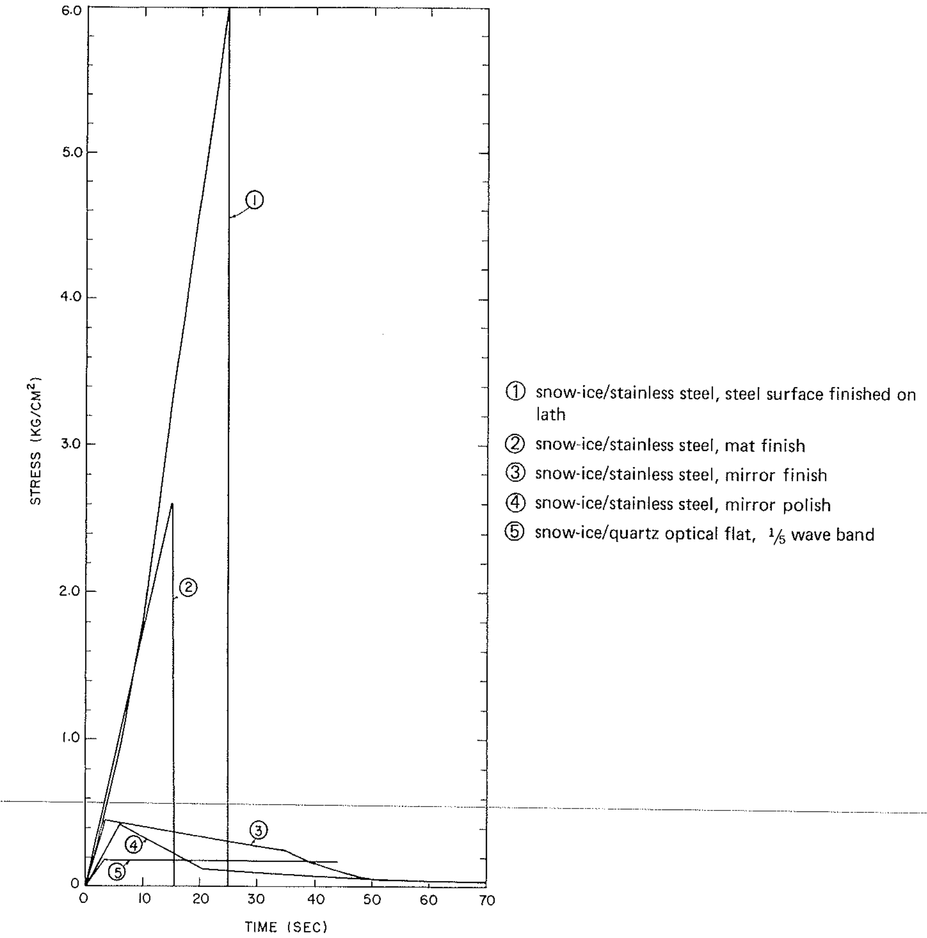


Figure 6. Typical stress versus time curves for stainless steel disks of different roughness and for fused quartz optical flat, -4.5 C (43, Fig. 2). Rates of shear are similar in all cases.

a slightly smaller slope than in the first experiment. However, after the maximum value, the stress drops quite slowly (the ice glides on the substrate surface) and eventually reaches zero or almost zero stress. An experiment was also carried out with an optical quartz flat as substrate. Here the stress rises still more slowly to 0.2 kg/cm^2 after which it remains constant with time; steady travel (gliding) of the ice over the quartz surface takes place.

7. A number of tensile experiments were performed using mat and mirror-polished stainless steel. The types of cohesive breaks obtained were similar and of similar magnitude as those obtained previously. The mirror-polished steel showed a somewhat smaller value for the cohesive strength. The mean tensile strength for mirror-finished sheets was 9.9 ±1.7 kg/cm^2 (-4.5 C, area 3.14 cm^2, height 1 cm). For mat finish, a value of 12.2 ±3.2 kg/cm^2 was obtained.

8. Shear experiments as a function of rate of shear were also carried out. The adhesive strength increases linearly with rate of shear (-4.5 C, snow-ice/mirror-finish stainless steel). The relationship is as follows

$$\bar{S}_A = 69.9v + 0.22 \tag{24}$$

where v is the rate of shear in cm/sec. It is interesting to note that this straight line has an intercept on the adhesive strength axis of 0.2 kg/cm^2, the same value as that obtained with optically flat quartz (Fig. 7).

9. Quite a number of experiments were carried out with optically flat quartz as substrate (flat within one-third of a light band). The ice cross section was made somewhat smaller than the quartz area to allow for movement of the ice or vice versa.

Adhesive strength was measured as a function of average rate of travel of the quartz flat (cm/sec). Ice was snow-ice (0.888 g/cm^3, -4.5 C, area about 5 cm^2, height 0.1 to 0.2 cm). At least 11 tests were made for each rate of travel. The results are given in Table 7.

The adhesive strength plotted against the rate of shear gives a straight line with an intercept for zero rate of shear at about 0.07 kg/cm^2. The equation for the straight line is

$$\bar{S}_A = 15.1v + 0.07 \tag{25}$$

where v is rate of shear in cm/sec (Fig. 8).

10. Tensile tests were also carried out with optical quartz flats as substrates (height 1 cm, diameter 2.3 cm, -4.5 C). Breaks were cohesive and similar to those

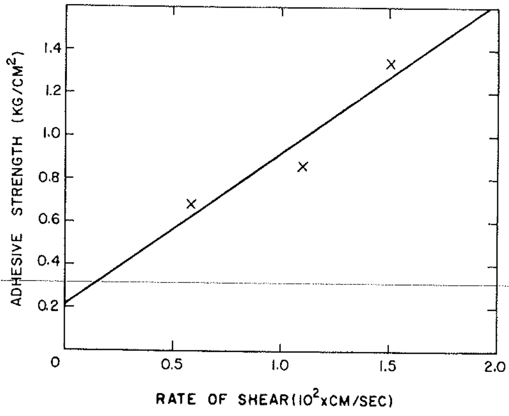


Figure 7. Relationship between average adhesive strength and rate of shear for snow-ice/stainless steel, mirror polish, -4.5 C (43, Fig. 3).

TABLE 7

ADHESIVE STRENGTH OF SNOW-ICE/OPTICAL QUARTZ FLAT AS FUNCTION OF RATE OF TRAVEL

Average Rate of Travel (cm/sec)	Mean Adhesive Strength (kg/cm^2)	Standard Deviation (±kg/cm^2)
0.53×10^{-3}	0.074	0.020
1.10×10^{-3}	0.120	0.059
6.30×10^{-3}	0.184	0.083
1.20×10^{-2}	0.194	0.063
1.60×10^{-2}	0.355	0.105
2.50×10^{-2}	0.402	0.130
4.10×10^{-2}	0.720	0.190

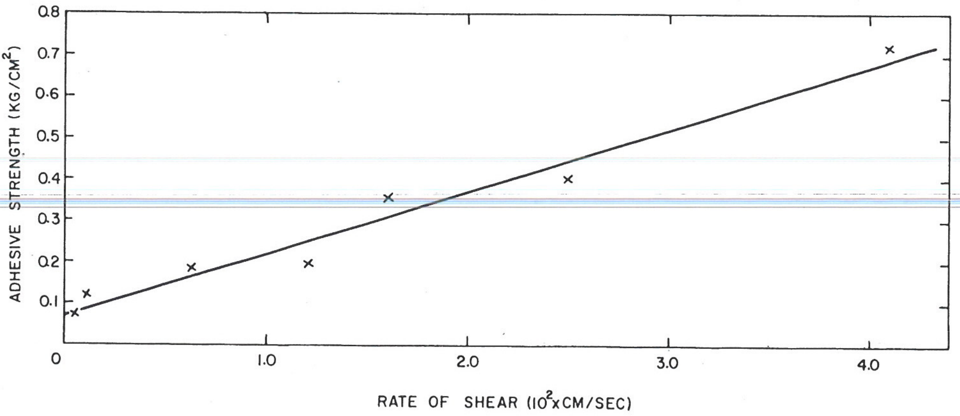
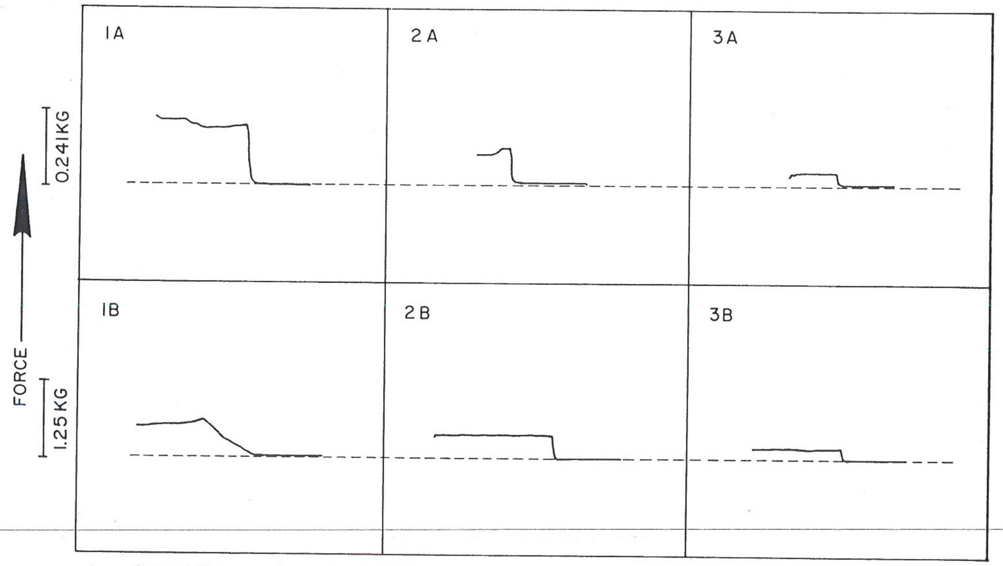


Figure 8. Relationship between average adhesive strength and rate of shear for snow-ice/fused quartz optical flat, -4.5 C (43, Fig. 5).

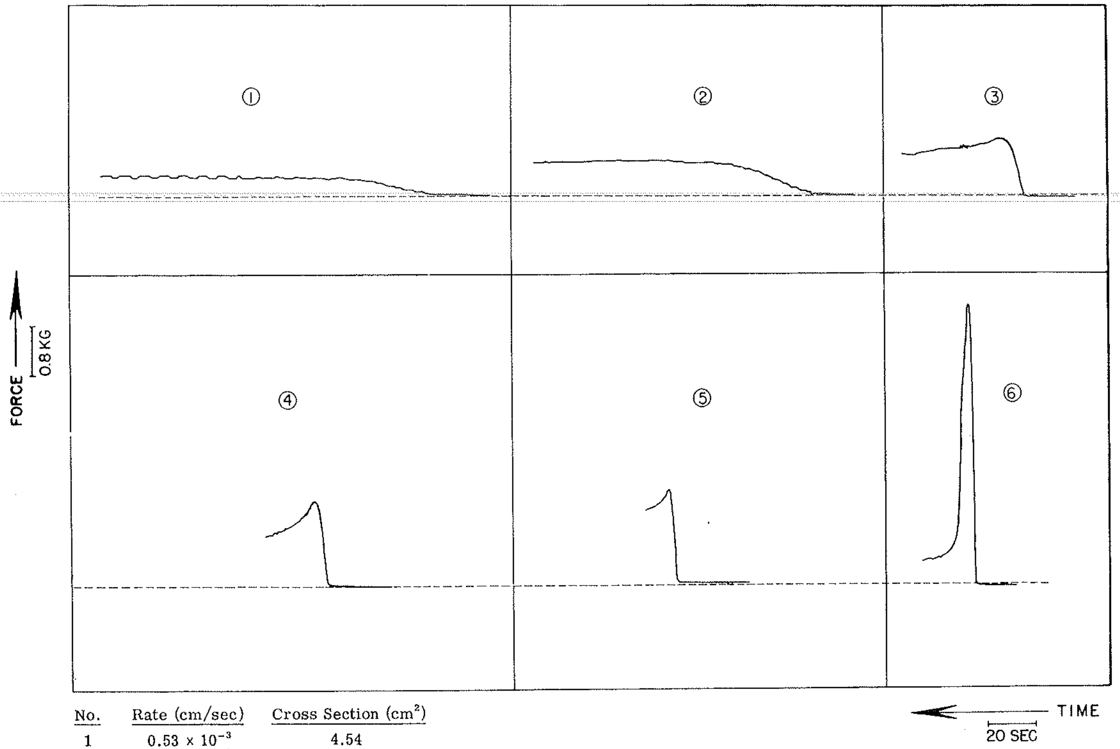
obtained with stainless steel. The mean tensile strength amounted to 10.6 kg/cm^2 with a standard deviation of ±2.7 kg/cm^2.

11. Frictional properties of thin water films sandwiched between optical flat glass plates were investigated (44). One of the plates was slid very carefully over the water film. The thickness of the films was measured by optical interference and ranged from 0.2 to 1μ (0.2 x 10^{-4} to 1 x 10^{-4} cm). The shear stress at constant shear rate



No.	Rate of Shear (cm/sec)	Approximate Thickness (μ)
1A	0.0118	0.85
2A	0.023	0.96
3A	0.033	1.4
1B	0.00074	0.59
2B	0.0075	0.86
3B	0.0118	0.51

Figure 9. Recordings of force versus time for water films between glass plates, -5 C (44, Fig. 13).



No.	Rate (cm/sec)	Cross Section (cm^2)
1	0.53×10^{-3}	4.54
2	1.1×10^{-3}	4.24
3	1.2×10^{-2}	3.93
4	1.6×10^{-2}	4.84
5	2.5×10^{-2}	4.59
6	4.1×10^{-2}	4.84

Figure 10. Typical recordings of force as a function of time at different rates of shear for snow-ice/fused quartz optical flat at -4.5 C (43, Fig. 6).

was found to be a linear function of the reciprocal film thickness. The frictional force dropped rapidly for thicknesses larger than 1 μm to such low values that they could not be recorded with the equipment available. Recordings of force versus time are very similar to the recordings obtained with ice-quartz; at high rates of shear a very sharp maximum was quickly reached, whereas at low values lines almost parallel to the time axis are obtained (Figs. 9 and 10).

Comparing the plot of stress versus reciprocal thickness of the water film at -5 C obtained for a rate of shear of 0.0114 cm/sec with the results for quartz/snow-ice gives a thickness of water film of 0.2 μm behaving almost the same as the snow-ice/quartz at -4.5 C.

DISCUSSION OF TESTS

The general features of ice adhesion found by the various investigators are similar in general outline and type, although they differ in some details and in their numerical values. Cohesive breaks using uncovered metal substrates were generally found in tension experiments; also, the observation that monolayers are not sufficient in changing cohesive to adhesive breaks is also a general feature. Thicker coatings, however, give rise to adhesive breaks. Lubricants alone are also not very effective unless surface active agents are added, but this addition is not necessary for hydrophobic surfaces such as polytetrafluoroethylene (Teflon).

The increase of tensile strength with decreasing ice volume is part of a general property of materials. Height and cross-sectional area are also generally found to have an effect on the strength. Those polymers that have been investigated in tension and shear usually show adhesive breaks that are temperature dependent; cohesive breaks are not or are only slightly dependent on temperature. Adhesive breaks with polymers or coatings as substrates often give an indication that the break has really taken place very near the interface in the weaker material (usually the polymer). Thus, in the strict sense of the word, cohesive breaks take place—temperature dependence of these breaks also suggests that. However, the macroscopic appearance of the breaks gives the impression of an "adhesive" break. It is doubtful whether adhesive breaks actually can take place at all. For convenience, one talks about cohesive and "adhesive" breaks, even if the latter are most likely "special" cohesive breaks, which probably take place within about one monolayer of the interface. There is no exact correlation between contact angles of water and various substrates, but the general trend is roughly followed, namely that hydrophobic substrates (θ large) give relatively low strength values, while strength values increase with the hydrophilic nature (θ small) of the substrate. Stress concentration, thermal expansion, and conductance effects were found by all workers. The history of the ice influences the numerical values obtained, but the type of relationship is often preserved.

The most remarkable feature in ice adhesion work is the very large strength differences found for tensile and shear experiments. This will be discussed later; a detailed discussion was given in a previous paper (45, 46). The shear experiments are characterized by the following features: The adhesive strength decreases linearly with temperature for stainless steel substrates; however, at a certain temperature the adhesive breaks change quite suddenly to cohesive breaks, which are only very slightly temperature dependent. This occurred at -13 C for Jellinek's tests (24); Hunsacker et al. (34) observed this at about -12 C and Raraty and Tabor (29) at about -7 C. Quartz-ice joints give the definite impression of ice gliding across the quartz surface or vice versa. This glide can be accomplished by almost zero rate of shear application. If the stress rates are increased, the impression is gained that the system cannot relax quickly enough and a fairly fast release (break) is observed.

Tensile strength experiments on bare metals and on optical flat quartz surfaces as substrates show cohesive breaks of normal magnitude. If the ice volume is made small enough, of the order used in many of the shear experiments, the tensile stress increases enormously. In Jellinek's experiments 70 kg/cm^2 were reached, but there is no reason why still higher tensile strength values could not be obtained. It is impossible to explain these profound differences of tensile and shear tests by easy creep of solid ice along the substrate interface and by very much less creep in the ice perpendicular to the interface. This does not actually throw any doubt on the replica technique observations made by Bascom et al. (19). However, it must be concluded that their technique is not suitable for solving the problem encountered here. The replica method actually misses the clue for this discrepancy as will become clear in the following.

Ackley and Itagaki (20) also investigated defects in the transition zone during adhesion processes and came to the conclusion that this zone is crowded with defects. Murrmann, Anderson, and Peek (21) studied the ionic surface diffusion of ice. These authors attempted to combine the various views concerning the nature of the transition zone. Thus, they suggest that it starts with bulk ice, then goes over into a region rich in defects and misorientation and eventually nears the properties of water in its uppermost ranges. This seems to be a reasonable and fruitful approach. One type of experimental method can only detect the defects, missing the more liquid-like part, whereas other methods can mainly locate the liquid-like part and not the defective zone. It is very likely that both parts are present in the various regions of the transition layer and there is no real contradiction between these apparently opposing views.

The assumption that actually accounts best for all the observed facts regarding the difference of tensile and shear experiments is that of a viscous or plastic transition layer in the ice-air and ice-solid interfaces respectively in the range from the ice melting point to lower temperatures. The properties of this layer are dependent on the particular ice-solid interface as far as thickness, viscosity, temperature range, and the like are concerned. In this way, the vastly different behavior of ice-solid systems on tension and shear can be accounted for. This assumption was treated in detail in a previous paper and its exhaustive discussion will not be repeated here. The term "liquid-like," used previously, led to some misunderstandings in the past and is best to be avoided. Hence, we refer here rather to a viscous or plastic transition layer. This means that there is a gradual transition from bulk ice or far from the interface to water-like substance at the interface itself. The side of the transition layer directly adjacent to the substrate surface resembles liquid water more than ice. A molecular structure different from water or ice, such as the case for so-called "anomalous water" discovered by Derjaguin (47), is not envisaged here. Actually, Hori (49) in 1956 seems to have experimented with such anomalous water without realizing its real significance.

The picture of such a transition layer does not contradict any of the results of other ice research workers. It is also not intended here to go into any detailed history of this transition layer, which originated with Faraday (50, 51, 52, 53) in 1856 and the phenomenon of regelation. Such famous scientists as the Thomson brothers, Lord Kelvin (54) and J. Thomson (55), Tyndall (57), and Helmholtz were involved in a controversy about pressure melting of ice. This type of melting cannot be involved here (590 atm are needed to depress the melting point of ice to -5 C). Jensen (58, 59) presented quite conclusive evidence against pressure melting in this connection. Bowden and coworkers (60, 61, 62) discussed melting by friction. There is, of course, a possibility of obtaining melting by friction in shear experiments, if the stress rates are very high. However, this possibility recedes more and more the slower the stress rate, and can safely be excluded for small rates. In more recent times, Weyl (63) wrote a theoretical paper on the transition layer and Nakaya and Matsumoto (64) were the first to present experimental evidence for such a layer. Thus, in summary, the different properties of tensile and shear tests can be explained as follows: A cylindrical ice specimen adhering to stainless steel as substrate, for instance, has a transition layer of definite thickness that depends on the temperature (Fig. 11). It is assumed that this layer forms a zero contact angle with stainless steel. On tension a pressure difference due to the curvature of the transition layer has to be overcome; its magnitude is (4, 65)

$$\Delta P = \gamma_t\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{25}$$

Here ΔP is the pressure difference across the transition layer-air interface, γ_t is the transition layer surface tension, and r_1 and r_2 are the radii of curvature, $r_2 >> r_1$; hence,

$$\Delta P = \frac{2\gamma_C}{d} \tag{26}$$

where d is the diameter of the smaller curvature. Hence, if d is small enough (about 10^{-6} cm at -5 C), the ice ruptures cohesionally long before adhesive failure can take place ($\Delta P = 7 \times 10^7$ dyne/cm^2, $\gamma = 76.4$ dyne/cm). However, in shear, only viscous or (if non-Newtonian) plastic forces have to be overcome in the transition layer. If the surface of the substrate is smooth enough, as is the case with optically flat quartz, the smallest stress will cause continuous gliding of the ice across the substrate as is actually observed with quartz-ice. There may be a small yield point needed to overcome the structure of the transition layer. All experiments reviewed in this paper can be

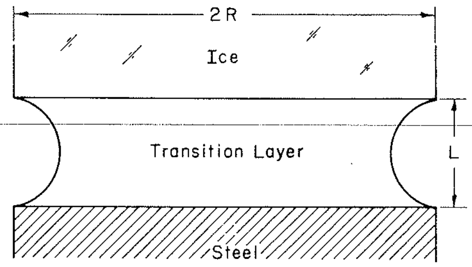


Figure 11. Transition layer between ice and solid substrate, metal or polymer (46, Fig. 9).

explained consistently on this basis. The average viscosity of the transition layer was estimated for ice-steel at about 70 to 700 poises and for ice-quartz, 15 to 150 poises for a layer thickness of 10^{-5} to 10^{-6} cm, at -4.5 C.

Quite a number of papers were discussed previously (45, 46), which add evidence for the existence of such a transition layer. This discussion will not be repeated here; however, some of these papers and some new ones will be mentioned briefly. In addition to those of the last century, the contributions of Weyl (63), Nakaya and Matsumoto (64), and Jensen (58, 59) were already mentioned. Jellinek and Ibrahim (66) sintered very small (radii $0.5\ \mu$) ice spheres at various temperatures, following surface area changes by the BET method. The results are compatible with the assumption of a transition layer. Kingery (67) also carried out sintering experiments, which are also consistent with the assumption of a transition layer. A paper by Telford and Turner (68) explains the slow migration of wires through ice in terms of the transition layer. Similar experiments were carried out by Townsend and Vickery (69) and by Nunn and Rowell (70). The results do not agree with Nye's theory (71) of regelation based on pressure melting. The latter came to the conclusion that regelation based on pressure melting shows many discrepancies with experimental data. Mason, Bryant, and van der Heuvel's paper (72) on growth habits and surface structure of ice crystals is of relevance here.

Fletcher (75) was the first to elaborate the existence of a transition layer on thermodynamic grounds. His first treatment contained some fairly rough approximations. Since then, he has revised this theory (78, 79). New information on quadrupole moments of water molecules and on liquid water structure has been utilized. Electrostatic forces are taken into account in this revised paper. The main driving force for molecular orientation near the water surface is the interaction between quadrupole moments and molecular dipoles. As far as ice is concerned, the free energy available from surface polarization leads to a change of phase in the ice surface over a range of temperatures near the melting point. The conclusion is reached that at temperatures larger than about -5 ± 3 C a transition layer exists on ice. Its thickness is calculated as about 10 to 40 Å at -5 C, increasing rapidly with temperature (Fig. 12). The electric conductivity of this layer is quite large, based on this theory. It may also be mentioned here that Jellinek and Nagarajan (80) carried out some rough contact angle

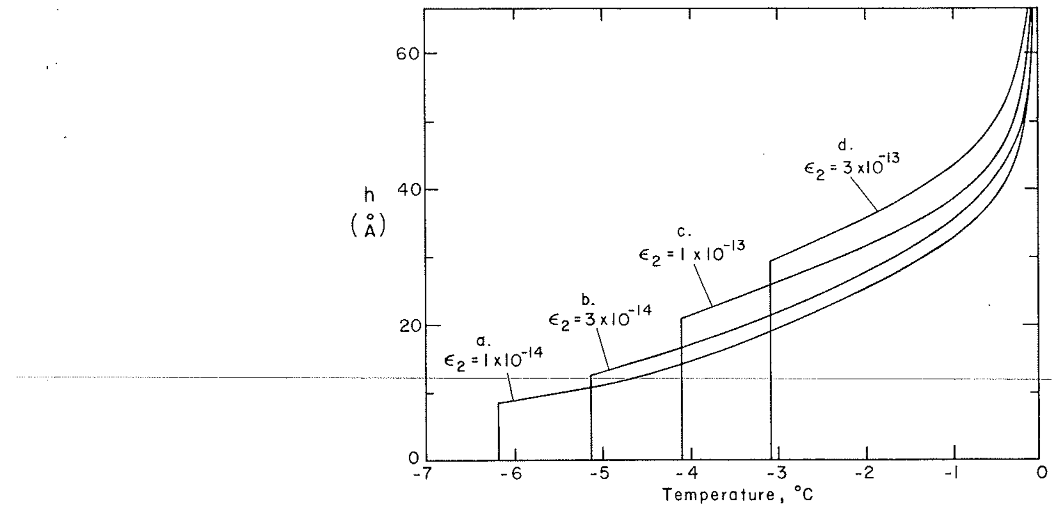


Figure 12. Calculated transition layer thickness on ice, h, for various assumed values of ϵ_2, energy of formation of diffuse L defects at the ice-water interface (78, Fig. 2, p. 1287).

measurements with paraffin and carbon disulfide on ice. These angles did not change over a large range of temperatures down to liquid nitrogen temperature. It is possible that, even on disappearance of the transition layer at lower temperatures, the uppermost water molecule layer does not take up a random arrangement again. The size of the contact angle is practically conditioned only by the first surface layer.

ICE ABHESION

There appear to be about 3 possible modes of attack on the problem of ice abhesion. In some respects, considerable success has been achieved in formulating effective ice releasing compositions and surfaces. But, there still may be room for improvement in certain areas. The 3 approaches to the ice abhesion problem, which can be pursued and which under favorable conditions may reinforce each other, are as follows.

Self-healing films have surface active additives that diffuse preferentially into the interface between the substrate and ice, forming highly condensed hydrophobic monolayers. If such a layer has been removed because of repeated abhesions, it can reform by diffusion of an additional agent from the bulk film to the interface. The main problem here is the role of diffusion, whose magnitude is dependent on the viscosity, structure, and temperature of the film. The second and third alternatives are somewhat similar. Decrease of shear strength of the layer near the ice interface in the substrate can be achieved by a liquid-like or pasty layer such as an oil or a grease, which has low shear strength. These substances should preferably be hydrophobic and often contain surface active agents to decrease interfacial free energies. Appreciable success has been achieved with such systems. Weakening of mechanical (shear) strength of ice near the interface can be achieved by inorganic and organic substances added in small amounts to the substrate. These compounds are soluble in water and pass preferentially into the crystal grain boundaries, enlarging the latter and weakening the ice structure. These 3 aspects of ice abhesion are discussed in detail in the following sections.

Self-Healing Films

Perfluorolauric acid gives the lowest CST, γ_C, value known so far. The surface, in this instance, consists of a closely packed condensed monolayer of -CF$_3$ groups. Unfortunately, these layers are removed on repeated abhesion and are only effective a limited number of times.

However, there is a way of regenerating such a monolayer; so-called "self-healing" films can be prepared. The same principle is operative here as that encountered in the formation of monolayers on water surfaces. To obtain a monolayer on a clean water surface in a Langmuir trough requires that molecules be spread on such a surface. These molecules must have such a structure that there is a sufficient balance between the water-soluble (polar) part of the molecule and its water-insoluble chain (hydrocarbon) part. If this balance is right, a monolayer is formed on the water surface. The polar groups dip into the water and the hydrocarbon tails stick almost vertically out of the surface in the monolayer, if it is closely packed. Thus a hydrophobic surface is created. The surface area occupied by each oleamide molecule, for instance, in a closely packed monolayer, is 28 Å^2. Water is not necessarily the only surface on which monolayers can be formed. Polymers can also have highly condensed monolayers on their surfaces, for instance, polyethylene (carefully protected from surface oxidation). Allan (81) has demonstrated the formation of monolayers on polyethylene by surface active agents. Such agents must have the right balance between polar and nonpolar groups. Examples of molecules are stearamide, oleamide, palmistamide, and myristamide. Oleamide was found to be the most effective in this group. The agents are either milled into the polymer or are present in polymer solutions from which films are cast. The polar groups are oriented toward the medium of higher dielectric constant (i.e., polyethylene). The free energy of the system becomes a minimum for such a configuration.

The amount of surface active agent for a given amount of polymer has to be increased if the surface-volume ratio increases or if the film thickness is decreased. Thus for

TABLE 8

VALUES OF CONTACT ANGLES FOR WATER

Surface and Additive	Polystyrene^a	Polymethyl-methacrylate^b	Polyvinylidene Chloride Copolymer (20 percent PAN)^c
Pressed disk, no additive	93	80	81
Solvent-evaporated surface			
No additive	96	94	85
Cleaned surface		76	
0.2 percent additive I		96	
0.5 percent additive I		96	
1 percent additive I			86
0.5 percent additive II		96	
1 percent additive II		97	
10 percent additive II	97		
40 percent additive III	96		
1 percent additive IV			100

[a] There was no change in contact angle for 1 percent w/w of additives other than for II and III; also the 2 latter additives were not very effective in polystyrene. Their solubilities are not high enough, and quite frequently another phase appears.

[b] I and II are sufficiently soluble in PMMA to show an effect. The cleaned surface of this polymer gives a contact angle usually found for PMMA.

[c] IV is very effective.

a film 50 μm thick and containing 100 ppm oleamide, a closely packed monolayer is formed on the polymer surface; however if this thickness is decreased to 25 μm, the amount of agent is not enough to form a complete monolayer. The rate of diffusion of such active agents to the polymer film surface is unfortunately slow under ordinary conditions. It can be accelerated by decreasing the polymer viscosity and by heating.

Allan's experimental results (81) can be summarized as follows: The agent diffuses through the film to the polymer surface until adsorption equilibrium is reached. A monolayer is formed within 1 to 500 hours depending on the viscosity of the medium. In the early stages, when the monolayer is not complete, some polar heads may actually point away from the polymer surface, increasing its hydrophobic nature.

A relevant paper was recently published by Jarvis, Fox, and Zisman (82). Fluorinated compounds were used on polymer substrates, which actually show a balance between their oleophobic and hydrophobic nature. The following is a list of partially fluorinated compounds used as surface active agents.

I. Tris (1 H, 1 H-pentadecafluoro-octyl) tricarballylate,
II. 3-(Hydroxymethyl)-1, 5-pentanediol tris(heptafluorobutyrate),
III. Bis (1 H, 1 H-undecafluorohexyl)-3-methyl glutarate,
IV. Bis (1 H, 1 H-pentadecafluoro-octyl) tetrachlorophthalate,
V. 1 H, 1 H-pentadecafluoro-octyl ethanesulfonate,
VI. Bis (1 H, 1 H-heptafuorobutyl) adipate,
VII. 18, 18, 19, 19, 20, 20, 21, 21, 22, 22, 22-undecafluorodocosanoic acid, and
VIII. N, N, N-dimethyl-3-(n-perfluoroheptanecarboxamido)propyl-3-aminopropionic acid, inner salt.

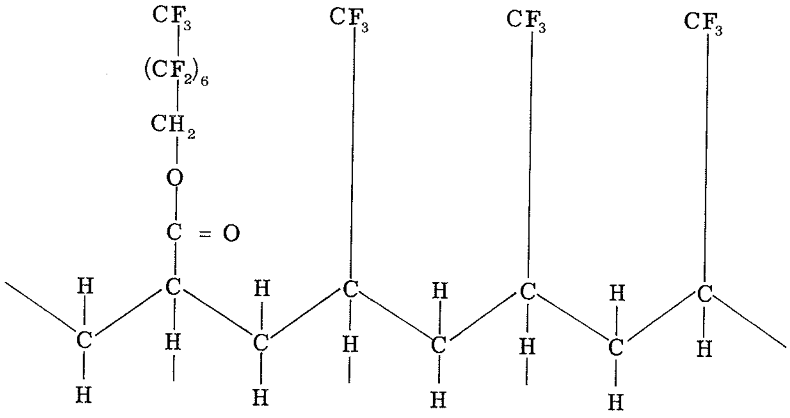
Four polymers were chosen as substrates: polystyrene (PS), polymethylmethacrylate (PMMA), polyacrylamide (PA, water soluble), and polyvinylidene chloride (PVeC) copolymer containing 20 percent polyacrylonitrile. The CST, γ_C, ranged from 30 to 33 dynes/cm for polystyrene to 40 dynes/cm for PVeC. The polymers were thoroughly purified and traces of solvent were removed by continuous pumping for 16 hours at room temperature. Films were prepared by slow evaporation of toluene. Contact angles were measured at 25 C.

The values of the contact angles for water ($\gamma = 72.6$) only are given in Table 8 (82). Disks were either pressed or cast from solution containing additives. Also, films with a number of different additives were prepared. Table 8 gives the results.

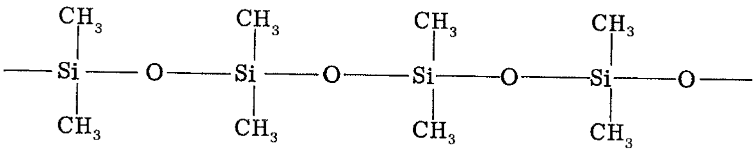
The films on these polymers should be self-healing. The efficiency in this respect, as repeatedly pointed out, depends on the bulk viscosity of the polymer. Fluorinated agents such as those employed in Allan's work give the lowest critical surface tensions, γ_C, as the surfaces are composed of $-CF_3$ or $-CF_2$ groups.

An interesting study of self-healing films was undertaken by the American Association of Textile Chemists and Colorists, Piedmont Section (83). Water-repellent films were mixed with fluorocompounds as surface active additives. These fluorochemicals are oil and water repellent. "Quarpel," for instance, which was developed by the U.S. Army Quartermaster Corps for textiles, consists of a pyridinium fatty water repellent containing a fluorocarbon. This study of textiles was based on Zisman's research (1) resulting in the formulation of critical surface tensions, γ_C.

It was recognized that a most effective fabric treatment would consist of producing a closely packed monolayer of $-CF_3$ groups or of the somewhat less efficient $-CF_2$ groups. Only smooth, nonporous surfaces were investigated. The fluorochemical chosen for this investigation was FC-208, available as a nonionic emulsion containing 28 percent solids. Its structure is representative of types of compounds used commercially, and is most likely a polymer or copolymer of vinyl-perfluoro-acid or perfluoro ester of acrylic acid.



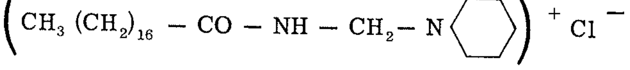
The silicone compound used was an emulsion of dimethyl and methylhydrogen siloxanes (Sylmer 72). The exact nature of this "silicone" has not been released, but it is of the following types:



$$-\overset{CH_3}{\underset{CH_3}{Si}}-O-\overset{CH_3}{\underset{CH_3}{Si}}-O-\overset{CH_3}{\underset{CH_3}{Si}}-O-\overset{CH_3}{\underset{CH_3}{Si}}-O-$$

Two fatty, wax-like water repellents were also employed in this work; these are generally applied in conjunction with fluorochemicals. The repellents were metallic soaps or film-forming polymers. Phobotex, FTC, a triazine fatty water repellent (TFWR) was also used in this research. It is a mixture of various fatty acids and alcohols attached somehow to methylolmelamine. Curing leads to cross-linking.

Last, a pyridinium-fatty-water repellent (PFWR) was chosen (Zelan AP). It is a pyridinium acid chloride derivative of stearamide, sold in the form of a preemulsified solid. The following structure is typical of this type of compound,



The emulsions were spread on the substrate and air dried (5 percent of total solids used). The films were then cured in an oven. Films of a number of substances were prepared by cross-linking various emulsions. Critical surface tensions, γ_C, were determined with alkanes.

Repellent	γ_C (dynes/cm)
Fluorochemical	13 to 16
Silicone	18 to 20
TFWR	about 21
PFWR	about 21

All these preparations are commercially available.

The CST values, γ_C, were plotted against the composition of the mixture; they decrease with decreasing fluorochemical concentration. TFWR is an exception; it shows a CST-minimum at about 0.5 percent w/w of fluorochemical. This may have something to do with the solubility of the fluorochemical in the film. Investigation showed that the 90-10 (TFWR-FC) mixture is uniform throughout the whole film, while the 99.5-0.5 mixture has most of the fluorochemical located at the film surface. The underlying substrate, glass or any other material, has no effect on the CST. If the surface of the film is abraded, the CST value increases. However, it can be decreased again by heating the film. Self-healing then takes place by reforming the monolayer by diffusion of the fluorochemical to the surface.

Decrease of Shear Strength in the Nonice Interfacial Layer (Lubrication)

This section deals with improper adhesive joints or with improper adhints. The latter term was coined by Bikerman (40). This approach to ice abhesion has been successful in many cases. An interfacial layer of relatively low shear strength such as an oil (lubricant) or grease is used to decrease the interfacial shear strength. In this category belongs also the transition layer on ice, which was dealt with at length in this author's fundamental studies on ice adhesion (42, 43, 45, 46). It is not necessary that a lubricant have a particular hydrophobic nature, although this is of advantage. The layer of oil, however, that is removed with each act of ice abhesion will probably be smaller if the oil is hydrophobic. The major condition is that the shear strength be low. Baker, Bascom, and Singleterry (84) studied the abhesion of ice from lubricated surfaces. Oil, to be really effective, should not be replaceable by water. Here again, addition of surface active agents up to about 1 percent is beneficial, decreasing the oil substrate interfacial tension. These additions appreciably decrease the adhesive strength of ice, for instance, in the case of diester oil (bis-2-ethylyl-hexyl-sebacate) on steel (-25 to -30 C). Barium-phenylstearate proved very effective, more so than phenylstearic acid. Additives did not, however, improve the Diester-Teflon surface. Mineral oil (Nujol)-Teflon also proved fairly effective without additive.

Quite extensive work was carried out by Plump and coworkers (85) with lubricated surfaces. A large number of substrates, oils, and additives were tried. The most efficient combination consisted of a silicone layer (Dow-Corning XZ8-3057) covered by pristane oil, a pure hydrocarbon found in sharks. Ice adhesion was very low for this system under various conditions tested in the laboratory and outdoors; the lubricant was effective for a number of abhesions. The rate of shear used in the laboratory apparatus was usually fairly high: 0.05 cm/min. Some results are given in Table 9.

A comparison of unoiled polymers and polymers oiled with pristane is of interest (Tables 10 and 11). These experiments were carried out at a shear rate of 0.5 cm/min. It seems that in the case of pristane also, the replaceability of the oil by water plays an important role.

Landy and Freiberger (27) also experimented with lubricants. A number of substrates were tested in the absence of surface active agents; in such cases the lubricated surfaces showed similar adhesive strength as the untreated surfaces. Only when surface active agents were added, a substantial reduction in adhesive strength took place. Thus only cohesional breaks were observed with bis (2-ethylyl-sebacate) alone; however, the addition of barium phenylstearate decreased the adhesive strength appreciably. The most efficient additive proved to be sodium di-nonyl-naphthalenesulfonate. Only adhesional breaks were taking place when this additive was present;

TABLE 9

SHEAR ADHESIVE STRENGTH OF ICE ON SILICONE XZ8-3507, LOT K2, OILED (PRISTANE) AND UNOILED

Rate (cm/min)	Temperature (deg C)	Strength (psi)	
		Oiled	Unoiled
0.005	-7.7	<0.10	4.1
0.05	-7.5	<0.15	5.5
0.5	-8.0	0.42	7.1
5.0	-7.3	1.50	2.8
0.05	-3.0	<0.45	3.4
0.05	-7.5	<0.15	5.5
0.05	-11.0	<0.41	>5.7

TABLE 10

UNOILED POLYMERS, -10 C, SHEAR STRENGTH IN psi

Freeze-on	Polyethylene (high density)	Polypropylene	Kel-F
1	<1.0	3.9	14.8
2	<10.0	13.7	10.4
3	3.9	11.7	—
4	5.5	14.1	—
5	<5.0	4.0	—
6	7.4	5.9	—
7	6.7	13.8	—
Avg.	<5.6	9.6	12.6

TABLE 11

OILED POLYMERS (PRISTANE), -10 C, SHEAR STRENGTH IN psi

Freeze-on	Polyethylene	Polypropylene	Kel-F
1	<0.1	<0.1	11.0
2	<0.1	14.1	<17.8
3	<<5.5	8.1	<19.7

the strength was reduced from 80 to 5 psi with steel as substrate. Also in the cases of brass and aluminum as substrates, the sodium compound was the most effective additive; however, a layer of bis (4′ -C_5) glutarate without any additive was found to be best for Teflon. Here again those additives that are effective prevent the displacement of oil by water, thus preventing wetting of the substrate.

In another series of experiments Teflon, polyethylene, and nylon were taken as substrates. The lubricants were various silicone greases and petroleum grease. Repeated abhesion tests were performed. Also additives were used in quite a number of cases.

The shear strength of ice for lubricated nylon, polyethylene, and Teflon was zero for several cycles of abhesion. After a definite number of cycles, however, the shear strength rises sharply if the surfaces are not relubricated. If a grease rather than an oil is used for coating these polymers, the number of cycles having zero adhesion increases.

During 12 cycles with polyethylene coated by silicone grease (J941-C5000), no increase in strength took place. Nylon is not so good. The number of effective cycles increases with decreasing temperature indicating that the higher the viscosity of the oil (within limits, of course) the more efficient it seems to be. Thus an oil should have a fairly high viscosity and a grease a high apparent viscosity index.

The general conclusion was arrived at that coating materials showing negligible adhesion with respect to ice must be liquid- or grease-like and must not be displaced by water or easily removed by repeated abhesions. These properties should not be too temperature sensitive. The nature of the solid substrate is also of importance, as it plays a role in the displacement of the oil by water. Hence, a low energy surface material such as polyethylene or Teflon is required. The reversible work of displacement of the oil by water is given by

$$W_D' = \gamma_{OW} (1 - \cos \theta) \qquad (27)$$

Equation 27 indicates that the greater the contact angle of water on the oil the more energy is needed to displace the latter by water. Maximum protection is afforded if $\theta = 180$ deg. The work of displacement of oil by water from a solid surface (Eq. 27) is also a function of the free surface energy of the solid. Baker et al. (quoted in 22) measured the effect of a number of sulfonate soaps on the contact angle of water on steel. They found, for instance, from Eq. 27, that $W_D' = 5.6$ erg/cm^2 for a sodium sulfonate and $W'_D = 20.5$ erg/cm^2 for a corresponding barium compound. In accordance with the theory, it was found that the barium compound is superior in reducing the adhesive strength of ice. Thus these surface active agents are adsorbed at the oil-solid (e.g., steel) interface. [There seems to be some contradiction to Ford and Nichol's (22, 23) results.]

Oil is not as easily displaced from polymers, i.e., from low energy surfaces, as from high energy metal surfaces.

Adhesion of ice to grease-coated metal surfaces is higher than that to grease-coated polymer surfaces. It is believed that water can, to some extent, penetrate the grease and wet the metal surface.

TABLE 12

ICE ADHESION OF 10^{-3} M SOLUTIONS ON VERY THIN WAX FILMS MEASURED AT -15 C

Solution	γ/cm^2	Solution	γ/cm^2
Distilled H_2O	4,250	$MgAc_2$	850
$SnCl_4$	2,800	Glycerine	790
NH_4Cl	2,775	Na-Silicate	770
NaCl	2,400	KAc	750
Calgon	2,375	$CaAc_2$	750
$BaCl_2$, pH 2.6	2,250	NH_4Ac	700
KCl	2,200	K_2SO_4	690
Aerosol OT 100	1,940	$BaCl_2$	660
$BaAc_2$	1,665	$NaNO_3$	650
$Ca(NO_3)_2$	1,375	$CaCl_2$	390
$MgCl_2$	1,300	$Th(NO_3)_4$	110

Note: Solution bp about 0.005 C.

Weakening of Ice Near the Interface

Extensive work has been carried out on this by Smith-Johannsen (86). He found that small amounts of water-soluble compounds appreciably reduced the strength of ice adhesion. These substances have to be insoluble in organic materials such as waxes or greases. Instantaneous freezing is a requirement for minimum adhesive strength. Thus solutions were usually cooled to 0 C before rapid freezing. Table 12 gives the values for the adhesive strength of 10^{-3} M solutions frozen to very thin wax films.

New surface coatings were elaborated on the basis of these results especially for aircraft propellers. A number of surfaces were tested, such as untreated wood, General Electric Antipastes (No. 87 and No. 89), and Teflon foil. Impure ice looks quite opaque and cloudly in contrast to pure ice. The reduction of ice adhesion by impurities was observed both for hydrophilic and hydrophobic surfaces such as glass, aluminum, chromium, copper, and also for these surfaces treated with waxes and lacquers.

It is of interest to consider the freezing process of impure ice more closely. The salt solution follows the phase rule on freezing, i.e., the solution becomes more concentrated as ice is frozen out according to its phase diagram. Hence, as long as the temperature is above the eutectic, one has a definite salt solution in equilibrium with ice. Quick freezing produces small grains. It was found that in the presence of impurities the adhesion is small only if a fine granular ice is formed. On quick freezing, the impurity distributes itself evenly over the whole ice sample; in other words, the impurity is trapped in the many grain boundaries existing in the fine-grained ice. The distribution of grains does not depend on the impurity or its amount but only on the rate of freezing. However, the widths of the grain boundaries are dependent on the type of salt solution and its concentration. These widened grain boundaries weaken the ice structure and contribute to easy abhesion. If the temperature is lower than that of the eutectic point, the grain boundary will be solid. The adhesion below the eutectic temperature of the added salt is lower than that without the impurity, but considerably higher than for impurities above their eutectic points. Exothermic heats of solution, low eutectic temperatures, and high water solubility are usually favorable properties. The adhesion decreases with increasing salt concentration to about 10^{-3} M, and, as pointed out, the grain boundary width increases with salt concentration.

A great number of solvents and substrates were tested. The best substrate was Formvar for wet outdoor conditions. The salt and Formvar were finely ground to a powder (about 1 μm) of uniform size distribution.

Pounder (87) performed some interesting experiments on the mechanical strength of ice frozen from impure melts, and also of ice layers that were sprayed with contaminants. Small amounts of alcohols, ketones, and ethers are very efficient in lowering the mechanical strength of ice. Alginic and stearic acids are also effective. One gram

TABLE 13

FRACTURE LOADING PRESSURES OF IMPURE ICE

Additive in 25 Percent Alcohol Solution	P_F	Average Percent Deviation
Pure water (no alcohol)	1.000	9
20 ml of 25 percent C_2H_5OH	0.263	18
20 ml LiCl	0.139	15
20 ml methyl cellulose	0.180	8
10 ml sodium stearate + 10 ml PVM	0.185	0
10 ml PVM + 10 ml D-235	0.185	16
20 ml T-253	0.202	18
20 ml PVM	0.211	17
20 ml ethyl cellulose	0.221	12
10 ml sodium stearate + 10 ml D-235	0.224	6
10 ml PVM + 10 ml L-245	0.255	20
20 ml soluble starch	0.262	5
10 ml sodium stearate + 10 ml agar-agar	0.274	6
10 ml soluble starch + 10 ml D-235	0.288	3
20 ml sodium stearate	0.302	29
20 ml agar-agar	0.325	29
10 ml sodium stearate + 10 ml sodium alginate	0.345	28

of each additive was dissolved in 75 ml of water and 25 ml of industrial alcohol. Of the resulting solution, 20 ml was sprayed on water of 800 cm^2 surface area; the total volume of distilled water was 25.0 liters. The concentration of the additive was thus 2.5 grams of solid and 50 grams of ethyl alcohol for each cm^2. Freezing was carried out at about -25 C for 60 hours. Ice sheets of 7 mm thickness of pure water and 8 to 10 mm thickness containing various additives were obtained in this way. The results are given in Table 13.

Impure ice is opaque, and the top surface is slightly roughened. Here again, it was observed that the grain boundaries increased in width and were responsible for the decrease in mechanical strength of the ice. Thus these observations agree with those of Smith-Johannsen (86).

Recently Jones and Glen (88) found appreciable lowering of shear strength of single ice crystals due to the addition of small amounts of hydrogen fluoride. Fluoride ions can be incorporated into the ice lattice. A few ppm of HF are effective. Thus 0.03 ppm HF decreases the shear strength of ice by half. The effectiveness decreases with increase in temperature.

CONCLUSION AND SUMMARY

The fundamental aspects of ice adhesion have been studied quite thoroughly in the past. However, ice abhesion from a practical standpoint has to deal with quite different conditions from those encountered with fundamental studies carried out under laboratory conditions. Although, the principles operative for ice adhesion are also valid in practical tests, they are often completely obscured under actual practical conditions. Contamination of surfaces and removal of substances may take place. Hence, an approach has to be made with respect to the practical problem of ice adhesion by considering 3 main avenues of attack: (a) preparation of self-healing films, (b) formation of interfacial areas of low shear strengths (oils and lubricants), and (c) weakening of the mechanical strength of ice near the interface. These 3 approaches have been discussed in some detail. Quite a large measure of success has been reported in some of these areas, which will probably not be surpassed in the future. However, an important shortcoming of the systems so far used is apparent. The drawback is the relatively low number of abhesions that can be carried out with these systems before the adhesive strength starts to rise appreciably. This is due to loss of material on abhesion; it presents one of the main areas where more research is needed.

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Informal Discussion

H. R. Kivisild

We have actually made some tests on the commercial surfaces mentioned using actual field materials. The tests were conducted in the form of the shear tests mentioned by Professor Jellinek. The main aim was to find out the relationships between the adhesion of ice to structural surface, temperature, and the properties of the material. Some observations were available on ice slipping on concrete and steel structures, and we also had laboratory tests to verify our findings from the field. We ran tests with rough steel, which gave something like a constant effect, or a cohesive break, all the way through at a temperature range from quite cool down to roughly 0.1 to 0.2 deg from the freezing point. The experiments were not really suited to cover any higher accuracy in temperature measurements. These were followed by tests on corroded steel, concrete, abraded concrete, and freshly poured concrete right out of molds, untouched. We even tried various coatings, like coal tar epoxy coating on the steel surface, and they all came up to a more or less constant cohesive figure almost independent of the temperature or of the properties of the surface. Only when we polished the steel surface was there a change with a rise in temperature from about -20 to -10 C from cohesive break to adhesive failure, and the adhesive failure seemed to occur as in the lubricating layer mentioned. This phenomenon was only observed on very smooth steel faces. There was no comparable effect on rough surfaces, which showed little reduction in shear strength at the face with increasing temperature. I wonder whether the tests on commercial and polished surfaces are in disagreement with Professor Jellinek's earlier work or whether they actually fall in the same pattern.

Jellinek

That is very similar to the work that I have done. If you measure the adhesive strength and shear of a smooth steel surface and go down in temperature, you get adhesive breaks down to -13 C. Then suddenly you get cohesive breaks, almost independent of temperature. Other people have also found this. Andecker at M.I.T., for instance, found this also at -13 C. Taking rate of loading, Raraty and Tabor in England found this at -7 C. If you take surfaces of various roughness, you can get something like this.

J. W. Renahan

What happens to the ice under compression?

Jellinek

How much compression?

Renahan

Any amount.

Jellinek

If you get too much, you get pressure melting.

Renahan

Then just enough compression to break the ice.

Jellinek

You get a certain compressive strength that is usually different from the tensile strength but not too much.

Renahan

I am referring to compression on top with this adhesion that is underneath.

Jellinek

I didn't do that, but I think you would get a cohesive break.

Renahan

In other words, would it move and break free?

Jellinek

It would not move because you have to press directly vertical to the substrate. The ice would break. You would get some movement in the ice, and you would get a cohesive break.

Renahan

Would it break the adhesive bond?

Jellinek

No, I do not think so. Before it melts, the cohesive strength will be reached.

Malcom Mellor

If we are talking about something like a roller running over a coating of ice on a solid substrate, I think we are dealing with a structural problem and the actual properties of the ice are secondary. Incidentally, I would take issue with the remark that the compressive strength and the tensile strength of ice are about equal. This is only true if you have a very poor loading technique.

Ionic Diffusion at the Ice-Solid Interface

R. P. Murrmann, D. M. Anderson, and J. W. Peek

Diffusion of ^{22}NaCl at the ice-aluminum interface was determined in investigating the nature of water at this junction. The average value of the diffusion coefficient of sodium ions, determined at 6 different times ranging from 8 to 28 days after introduction of the ions to the interface, was 9.4×10^{-8} and 4.5×10^{-8} cm^2/sec^{-1} at -5 and -10 C respectively. Comparison of these values with the diffusion coefficient for ionic diffusion in bulk liquid water, $D \cong 10^{-5}$ cm^2/sec^{-1}, and with that expected for ionic diffusion in ice, $D < 10^{-11}$ cm^2/sec^{-1}, indicates that the properties of the interface are considerably different from those of either bulk liquid water or ice. Lack of any consistent time dependence of the diffusion coefficient suggests that the nature of the interface was little disturbed by the addition of sodium chloride. These observations support the view that a transition zone 5 to 10 Å thick with liquid-like properties exists at this interface. A model of this concept of the ice-solid interface is proposed.

Development of methods for prevention or removal of adhering ice requires consideration of the factors that define each icing problem. A few of the most obvious and recurrent of these factors include the size and shape of the substrate surface, its physical location, micrometeorological conditions, and time and other economic considerations. Thus, a solution proposed for shipboard icing is not likely to be appropriate for treatment of aircraft wings, runways, power lines, windshields, antennas, refrigeration pipes, or roads. Faced with the diversity of icing problems and the different factors governing their occurrence, we might easily, if not inadvertently, deemphasize or overlook the essential aspects common to each. In attempting to create a condition at the ice-substrate interface that will preclude ice accumulation or facilitate ice release, we believe that an understanding of the nature of this interface is desirable and perhaps even essential, considering that up to now attempts to solve ice adhesion problems have with few exceptions resulted in limited success.

A few investigators of the phenomenology of ice adhesion have attempted to interpret their results in terms of the properties of the ice-substrate interface. Notable among several studies that have been undertaken from this point of view is that of Jellinek (8). He measured the shear and tensile strength of ice adhering to stainless steel, quartz, and several plastic surfaces directly. Although he found that cohesive breaks in bulk ice were common during the tensile experiments, adhesive breaks nearly always were observed with shear tests provided that the tests were carried out above -13 C. With decreasing temperature, however, shear strength increased until eventually only cohesive breaks occurred. To account for these results, Jellinek adopted Weyl's concept of a "liquid-like" interface (14), postulating that the properties of water there are intermediate between those of liquid water and ice. The specific properties of the interfacial zone were thought to be dependent on the nature of the substrate surface and temperature. Although Jellinek visualized a thickness of as much as 10^{-5} cm near 0 C, he felt that the thickness of the liquid-like zone surely decreased with decreasing temperature, accounting for the concomitant increase in adhesive strength. Jellinek explained the observed high tensile strength as being due to surface tension effects, whereas the relatively low shear strength was explained by the low frictional resistance of the liquid-like interface. This concept is supported by the results of many other types of experiments. Hoekstra (6), for example, has shown that glass beads embedded in ice migrate under the influence of a thermal gradient. This was explained as a consequence of a continual melting of ice and flow of water in a relatively thick film at the warm side of a bead to the cold side where refreezing occurs, thus advancing the position of the bead. Hoekstra also used a similar argument to explain the mechanism of particle exclusion by an advancing ice front. Telford and Turner (13) investigated the rate of movement of a steel wire under an applied load through ice as a function of temperature. Calculations showed that the pressure of the wire on the ice would cause a freezing point depression of about 0.5 C. In harmony with this prediction, the velocity of the wire through the ice was observed to increase markedly with an increase in temperature above about -0.5 C. Surprisingly, however, the wire moved through the ice at temperatures below -0.5 C, the velocity decreasing with decreasing temperature. Because this movement could not be accounted for by the conventional concept of "pressure melting," the authors presented their results as evidence for the existence of a zone of liquid-like water at the steel-ice interface. They attributed the temperature dependence observed to changes in visocity of the interfacial water that resulted from a concurrent decrease in film thickness and temperature.

At about the same time, Raraty and Tabor (12) reported the results of shear experiments to determine the adhesive strength of ice to metal and polymer surfaces. Qualitatively, their results were remarkably similar to those of Jellinek; however, a different explanation was advanced. For metals, they explained the temperature dependence of the shear strength on the basis of a change in ductility of ice in the region near the interface during what was viewed as a cohesive failure. In agreement with Jellinek, they reported brittle fracture of ice at lower temperatures. In the case of plastics, they did find evidence of a true adhesive break, but in either case Raraty and Tabor hold that the adhesion strength of ice results from a direct bonding of ice to the substrate.

Landy and Freiberger (9) investigated the shear strength of ice to a series of plastic substrates having a wide range of surface characteristics. Water surface tension, thermal expansion, porosity, dielectric constant, and flexural modulus of various substrates were correlated with the measured adhesive strength of ice. When the plastics were grouped on the basis of similar surface bonding characteristics, it was possible to obtain a correlation between flexural modulus and adhesive strength. Thus, it appeared that in the case of these materials the ice-substrate bonding strength was so strong that mechanical deformation of the substrate occurred. Also, the adhesion strength depended on the various types of ice-substrate bonds formed.

The nature and properties of the interface between ice and silicate substrates recently were discussed by Anderson (1). From several lines of evidence it was concluded that the interfacial zone is fluid with a thickness greater than 15 Å near 0 C to about 3 Å at temperatures of -10 C and below. At low temperatures the mobility of the interfacial water appears to be very much diminished, and it may even possess the properties of a glass. A phase diagram showing the relationships that exist among the interfacial water, water vapor, and ice also was presented together with a discussion of the effect of changes in temperature and pressure.

Most recently, Bascom et al. (3) investigated the shear strength of ice on steel, on steel covered with monolayers of various adsorbents, and on plastic-coated metal surfaces. To better determine the mechanism of failure, they obtained plastic replicas of the sheared ice surface to reveal fracture markings and crystal defects. The replicas indicated that the dislocation density near an interface was much higher than that of bulk ice, and it appeared that the glide plane of these defects was parallel to the interface. This observation provides an alternate explanation of Jellinek's finding that the ice-substrate interface appeared stronger in tension than in shear. The dependence of the ice adhesive strength on temperature and the nature of the substrate was partially accounted for on the basis that differences in thermal conductivity between various substrates might well influence the rate of accumulation of defects at the interface. Materials with a relatively low thermal conductivity would be expected to have more interfacial defects because the cooling rate from 0 C to a given test temperature would be lower allowing more time for defect accumulation. Taking this view of this evidence, Bascom proposed, as did Itagaki (7) earlier, that it is more appropriate to consider the ice-substrate interface as a defect-rich solid rather than as a zone with liquid-like properties.

Thus, it appears from this somewhat abbreviated treatment of the recent literature that, although there is a general agreement in a qualitative sense among the various investigators on the importance of factors such as substrate type, surface roughness, temperature, and surface contamination, there are 2 distinctly different points of view as to the nature of the ice-solid interface. Clearly research on the mechanism of ice adhesion should be directed toward resolving this problem. Jellinek (8) has suggested several useful approaches. This paper deals with one of them, the measurement of diffusion coefficients at the ice-solid interface.

The rate of diffusion of a molecule through a liquid or solid matrix depends on the energy barrier encountered in moving from one equilibrium position to another. For a given substance in the liquid state where short-range order with weak intermolecular bonding exists, the diffusion coefficient of a molecule is high relative to that for diffusion through the same crystalline substance where long-range order with strong bonding between adjacent molecules exists. Hence, one possible way of determining whether the interfacial zone at the ice-substrate contact is relatively thick and liquid-like on the one hand or solid-like with many lattice defects on the other is to measure the diffusion coefficient of some suitable substance confined in this zone and to compare the values thus obtained to those measured in known liquids and solids. This combined with the measurement of the adhesive strength of ice to the same substrates should provide a better understanding of the nature and characteristics of this interface. In this investigation we report preliminary values for the diffusion coefficient of $^{22}Na^+$ at the ice-aluminum interface to serve as a basis for more refined measurements.

EXPERIMENTAL

The substrate selected for this preliminary investigation was aluminum. This selection was made because aluminum is a common metal used in many applications in which ice adhesion is an important problem. To obtain a suitable configuration for the experiment, we used polished aluminum weighing dishes. Although the dishes were carefully cleaned to remove organic surface films and soluble salts, no attempt was made to remove or to prevent formation of aluminum oxide at the air-aluminum interface. Thus, the existence of an oxide layer may be assumed. Two sets of dishes were filled with distilled water to a depth of approximately 1 cm and frozen. One set was kept in a cold room maintained at -5 C and the other set was kept in a second room maintained at -10 C. Although some air bubbles were observed in the ice, the ice-aluminum interface was bubble-free. This simple method of preparing the samples was adopted after it was found that more elaborate methods did not seem to yield significant improvements. For example, considerable time was devoted to the development of a closed system for degassing the carefully cleaned surfaces prior to forming the ice-solid interface without exposure to the atmosphere. Although it was found that the shear strength of the ice-substrate bond increased and that the scatter in the data decreased slightly relative to values obtained by direct freezing in a cold room, the small improvement hardly warranted the elaborate effort required. The most important factor in obtaining reproducible shear strength values seemed to be the degree to which gross contaminants were removed from the test surfaces.

After equilibrating for 24 hours, the samples were treated as shown in Figure 1. The dishes containing the ice were inverted and a small hole was made through the aluminum in the bottom center of each dish by means of a dissecting needle. Next, a 1-μl aliquot of carrier-free, aqueous $^{22}NaCl$ solution having a total activity of about 0.05 μC was carefully introduced through the hole onto the ice by means of a 10-μl liquid syringe. Upon contacting the ice, the droplet froze upward, excluding $^{22}NaCl$ and leaving the isotope free to diffuse from the ice-air interface into the ice-aluminum interfacial region surrounding the point of deposition.

Use of a radiotracer keeps contamination of the interface to a minimum because the detection sensitivity of a radiotracer is very high. Consequently, a very small amount of tracer suffices. The proper choice of radioisotope depends primarily on the detection method that can be used for a given experiment. In any case, the radioisotope used should be in a carrier-free, high specific activity, neutral pH form. In this case,

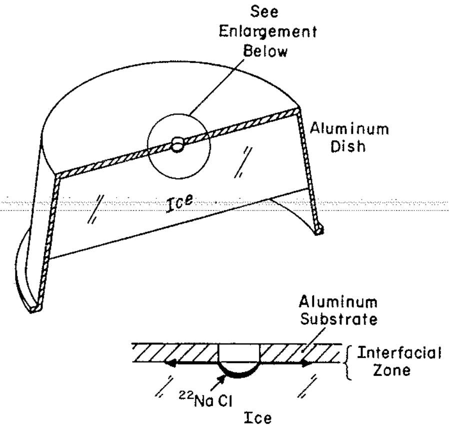

Figure 1. Application of ^{22}NaCl to the ice-aluminum interface.

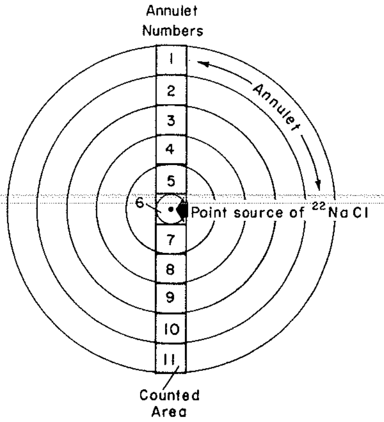

Figure 2. Determination of radial distribution of ^{22}Na at the ice-aluminum interface.

^{22}NaCl was a convenient choice because in the analysis the sample was sectioned and separated during counting so that gamma radiation from adjacent sections did not interfere with the measurement. If the sample could not have been sectioned, direct-counting or an autoradiographic method using a weak beta-emitting isotope might have been employed.

Diffusion was allowed to proceed for periods ranging from 8 to 28 days to check on the time-dependence of the diffusion coefficient. At appropriate times, samples were then transferred to a freeze-dry apparatus where the ice was sublimed away from the interface leaving ^{22}NaCl in place on the aluminum substrate. The aluminum dishes were carefully sectioned as shown in Figure 2. First, the side of the dish was cut away, and a strip 0.4 cm wide and 4.4 cm long was cut from the bottom of the dish. Each strip was then further subdivided into 11 segments 0.4 cm on edge. The center segment from the strip contained the hole through which ^{22}NaCl had originally been injected. The ^{22}Na activity of each segment was then determined by using a scintillation detector in conjunction with a timer-scaler. The radial distribution of ^{22}Na was found by calculating the total activity in an "annulet" from the activity of a given segment. As Figure 2 shows, this procedure resulted in 2 values for each annulet.

The boundary conditions of this experiment correspond closely to those defining diffusion outward from an instantaneous point source over an infinite planar surface. The solution of Fick's law for this case is given by Crank (4) as

$$C = \frac{M}{4\pi Dt} \exp\left(\frac{-r^2}{4Dt}\right) \tag{1}$$

where in this case C is the activity of ^{22}Na in cpm, M is the total ^{22}Na activity added as determined by summing the activities for each annulet in cpm, D is the diffusion coefficient in cm^2/sec^{-1}, t is time in sec, and r is the radial distance from the point of application to the center of a given annulet ring in cm. Inasmuch as Eq. 1 can be rewritten as

$$-\log_{10}\left(\frac{C}{M}\right) = \log_{10}(4\pi\, Dt) + \frac{r^2}{9.2Dt} \tag{2}$$

the diffusion coefficient of ^{22}Na$^+$ in the interfacial zone can be evaluated from the slope of a plot of -log (C/M) versus r^2. Although D can also be calculated from the intercept, there is more error involved because of uncertainty in the value for M.

RESULTS AND DISCUSSION

Plots of $-\log_{10}$ (C/M) versus r^2 made by using data obtained for 6 times ranging from 8 days to 28 days at both -5 and -10 C are shown in Figure 3. The lines drawn through the points represent a least squares fit. Although there is a fairly high degree of scatter in the distribution of data points for each experimental condition, it is clear that the data are best represented by a straight line as predicted by the model described earlier. The reason for the scatter is undetermined, but it could have been caused by a redistribution of ^{22}NaCl that may have resulted from sample handling or during the sublimation step of the experimental procedure.

The values of the interfacial diffusion coefficients calculated from the slope of the lines shown in Figure 3 are given in Table 1. At -5 C, the diffusion coefficients at different times ranged from 7.0×10^{-8} to 13.0×10^{-8} with an average value of 9.4×10^{-8} cm^2/sec^{-1}. Similarly, at -10 C, a range of 2.1×10^{-8} to 6.4×10^{-8} with an average of

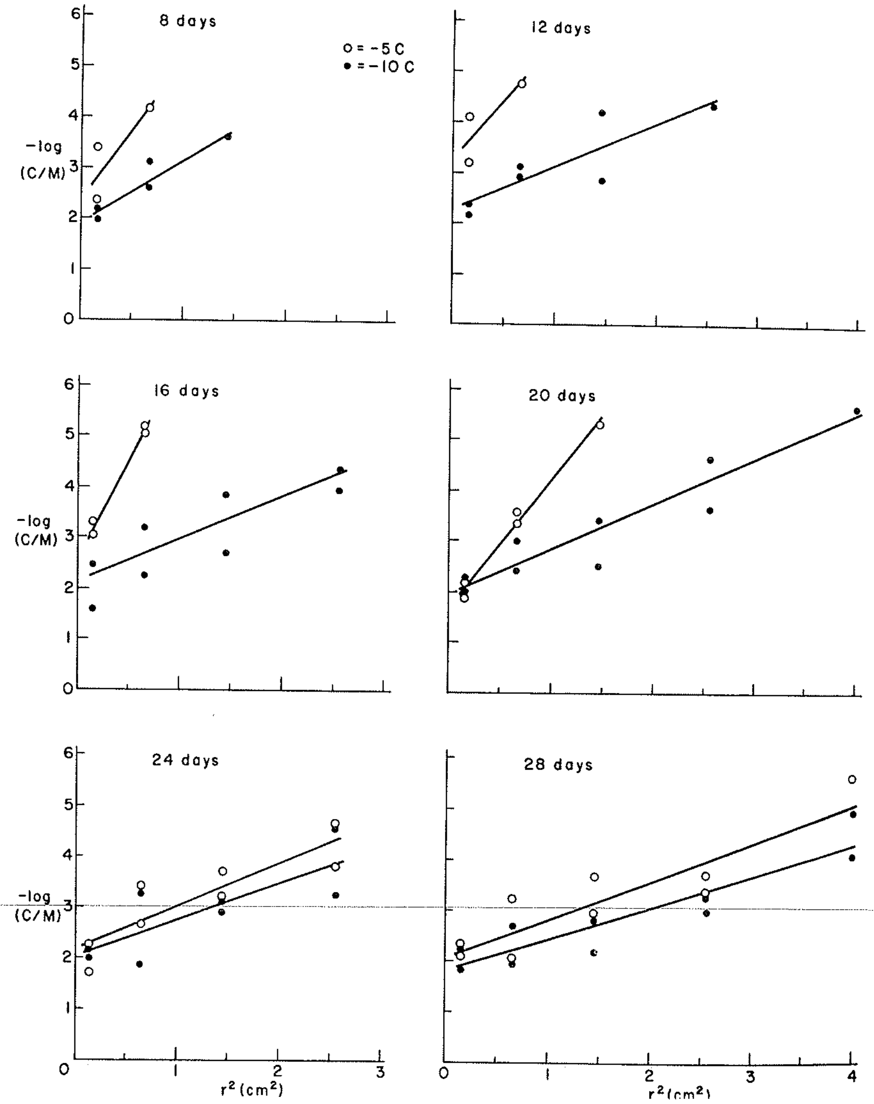

Figure 3. Calculation of diffusion coefficient of Na$^+$ at the ice-aluminum interface.

4.5 x 10^{-8} cm^2/sec^{-1} was observed. Thus, decreasing the temperature from -5 to -10 C decreased the value of the diffusion coefficient by about a factor of two. Lack of a clear-cut and consistent trend in the observed diffusion coefficient as a function of time suggests that the variation in values obtained at both temperatures arises from experimental error. For the experiment conducted at -5 C, even though the values do not change by more than a factor of two with time, the data given in Table 1 might indicate a real time dependence. If the trend is real, because diffusion obviously is more rapid at -5 C than at -10 C, it might be explained by a depletion of tracer at the source. It should be noted that if diffusion were a result of freezing point depression effects caused by the ^{22}NaCl solute, the diffusion coefficients would be expected to decrease with time because of progressive dilution. However, the lack of a strong time dependence supports the view that the added ^{22}NaCl did not appreciably disturb the interfacial zone.

TABLE 1

DIFFUSION COEFFICIENT OF Na^+ AT THE ICE-ALUMINUM INTERFACE

Time Following Application of ^{22}NaCl (days)	D x 10^2 (cm^2/sec^{-1})	
	-5 C	-10 C
8	13.0	5.7
12	12.5	4.5
16	9.4	2.1
20	7.2	2.4
24	7.0	6.4
28	7.2	5.9
Avg.	9.4	4.5

Values of the diffusion coefficients of a soluble salt in liquid water are of the order of 10^{-5} cm^2/sec^{-1} (5). Although the diffusion coefficients of salts in ice have not been determined, the values are not expected to exceed 10^{-11} cm^2/sec^{-1}, the value for the self-diffusion coefficient of water molecules in ice (11). The diffusion coefficient of Na^+ obtained during this investigation is intermediate to these values. The value obtained is, if anything, closer to that for diffusion in liquid water than that expected in ice. This finding indicates that Na^+ is highly mobile at the ice-aluminum interface compared to its mobility in ice. Although these results do not rule out either the liquid-like interface concept or the solid but defect-rich interface concept, it is clear that the interfacial zone possesses characteristics that definitely distinguish it from normal ice. Also, the observed diffusion rates are hardly compatible with a liquid-like interfacial zone several hundred molecular diameters thick as Jellinek (8) suggested might be present; they are too low. The diffusion coefficients obtained in this study are comparable in magnitude to those obtained by Murrmann et al. (10) in an earlier study of sodium self-diffusion in a frozen clay-water matrix. From the evidence advanced by Anderson (1), there can hardly be any doubt that the interfacial zone in the clay-water matrix consists of unfrozen, liquid-like water; and, as shown by Anderson and Hoekstra (2), the thickness of this interface at -5 and -10 C is of the order of 10 and 5 Å respectively. From this correspondence, it appears that if the ice-aluminum interface is viewed as also consisting of a layer of liquid-like unfrozen water, its thickness must be comparable, that is to say 5 to 10 Å. A representation of the ice-aluminum substrate that is compatible with this view is given in Figure 4. The diagram is drawn roughly to scale, but the thickness of the interfacial zone is slightly exaggerated to

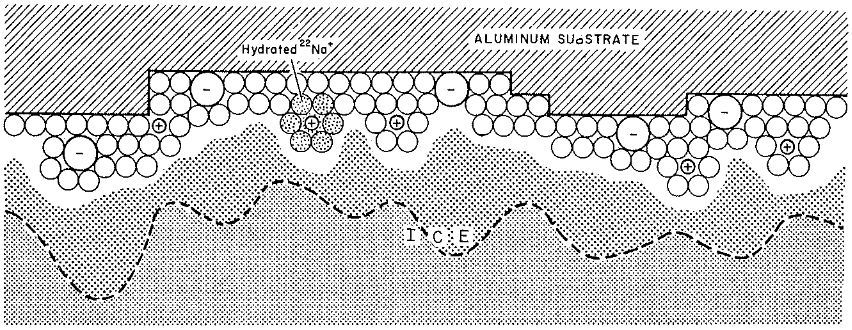

Figure 4. Schematic diagram of the ice-aluminum interface.

show the possibility of fully hydrated ions and a defect-rich zone in the adjacent ice. The soluble substances may be impurities but, in any case, are always present because of dissolution of the substrate interface. Although on the present balance of evidence, we favor the concept shown in Figure 4, it must be acknowledged that the data do not rule out the defect-rich solid interface concept of Itagaki (7) and Bascom (3). This controversy probably will not be resolved until the crucial experiments are done on substrates for which the surface roughness is known to be less than the presumed thickness of the interfacial zone, say 3 Å or less. Further work designed to decide this issue is planned.

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Informal Discussion

H. H. G. Jellinek

It is unfortunate that I used the term liquid-like layer about 15 years ago when some of this work was done. It would have been better to have called it a transition layer, meaning that there is a transition in coming from bulk ice to bulk water. Now, in his experiments, Bascom postulates a high number of defects in the interface. With that method you would not be able to determine any of the liquid interface; it would miss the transition layer altogether. But if there are no defects, of course, then it is a question of semantics as to whether you call that a transition layer or you call the liquid side the transition layer. I think the idea of starting with the defects and then going into a more liquid-like structure is the right approach. As far as the diffusion is concerned, we have recently measured the diffusion of radioactive cesium in polycrystalline ice, and at -6 C it is on the order of 10^{-10}. The diffusion coefficient is dependent on the concentration of the cesium. You have to consider 2 types of diffusion in polycrystalline ice: the bulk diffusion going through the ice grains and the grain boundary diffusion, which is the same type of diffusion as in metals. Mr. Murrmann shows that the diffusion coefficient depends on the time. We have measured the grain size distribution in polycrystalline ice. If you measure the distribution as a function of time, or the average diameter of the grain as a function of time, it increases with time—small ones disappear and the interfacial area becomes smaller—so the diffusion should get smaller as time goes on, and I think that is what Mr. Murrmann found.

Murrmann

We found that the diffusion coefficient did become smaller.

Jellinek

That means the grains become larger with time, and of course the boundary diffusion is slower than the grain boundary diffusion. There is less grain boundary as you go on in time. That is my explanation of the dependence of diffusion coefficient on time.

Murrmann

A second explanation, of course, is the fact that as you put a point source you are introducing a contaminant at the interface and this may effectively create a liquid-like layer itself. The effect of this would be that the diffusion coefficient would decrease with time because of the dilution that occurs with time. In another case at -10 C, it seemed to be constant within the experimental results that we had; so it is hard to make a point of this. This is certainly something that must be taken into consideration when an approach like this is used. The idea is to find under what conditions an interfacial zone exists or does not exist. The other point that Dr. Jellinek brought out is one that should be taken more seriously; that is, when do you start calling something defect-rich and liquid-like? This becomes a matter of debate, which is a waste of time as far as I am concerned. A great deal of evidence accumulated indicates that the molecules next to a surface, maybe not the adjacent molecules but the layer next to that, are highly mobile and also, in many cases, highly associated. Therefore, things happen in these layers of water very close to surfaces that you would not expect to happen in bulk ice—a surface chemical activity one might observe.

H.R. Kivisild

I agree that which of the ideas is right is really a point of semantics. Because we found out that the large effects of roughness could be explained by the assumption of a liquid-like layer and could not be explained by the assumption of interfacial deformation, we rather favor the change to a liquid-like form.

Jerrold L. Colten

Have you been able to determine any effect on rate of cooling of the substrate when you come down very rapidly in your freezing test? I am alluding to the rate of crystalline growth within the ice itself.

Murrmann

We have not studied this ourselves. We have in preliminary work drawn ice at different temperature and different cooling rates and tried to do some shear tests. Allowing an aging period of a day or two, we were not able to tell much difference. Others have investigated these different factors. I think that what is important apparently, judging from what other investigators report, is the fact that a recrystallization near the interface does occur, and that in making shear tests such as we did you must allow a sufficient period of time for this reorientation to occur near the interface or else it will occur during the course of the experiments and will shed some doubt on what you are doing.

Lorne W. Gold

Do you take into account in any way the possible thickness of the diffusing layer at the surface?

Murrmann

There is really no way to tell whether you are dealing with a thick layer or a thin layer. I can only mention what we have done with other systems that are colloidal minerals in which you can actually measure the thickness between adjacent clay plates. There is also other evidence that leads you to believe what the thickness would be between, say, clay plates and different minerals and ice surfaces. In these cases we have found that the diffusion coefficient is the same order of magnitude as I have pointed out. Also, we have been able to measure the thickness directly; actually it was done by Dr. Hoekstra and Dr. Anderson at USACRREL. In this case it turns out to be 10 Å units, or 9 units. The point I would like to make is that, if there is a liquid-like layer, we feel that very probably it is very close to the surface and very thin. Then it becomes semantics again where it ends in terms of the defect structure.

David Brohm

I would like to make an observation from the practical point of view. For many years, some excellent observations have been made by good practical people that road chemicals commonly used appear to act most beneficially in breaking the ice-to-pavement bond in the interface region. The practical point made by highway maintenance staff and by technical representatives of the firms selling winter ice control chemicals was the augur action of salt and calcium chloride in crystal form, which penetrated through the ice or snow layers to the interfacial region where it broke the ice-to-pavement bond. It is in this bond-breaking that we get the most efficient and most economical use of our chemicals.

According to Mr. Carey's remarks this morning, in some instances 35 tons of chemical per lane mile may be applied to a highway for winter ice control. Extend this to the 12- to 14-lane expressway and the aggregate exceeds 400 tons of chemical per linear mile. We can only describe this as an unacceptable level of environmental pollution. We propose additional research is most warranted to determine better ways to apply and use the chemical to optimize the bond-breaking mechanism to determine the minimum amounts of chemical necessary to give the necessary bond-breaking at the interface, and to develop all of these considerations as steps to optimum ice control with a minimum of pollution.

Murrmann

I hope that the main benefit to the sort of research that I have described here and what Dr. Jellinek has described in the past will create a better understanding of the problem. Things move faster when you understand what is going on. I am not proposing that this research will lead to a practical solution, though perhaps it can.

Jellinek

I mentioned in my paper that very small amounts of inorganic chemicals decrease the mechanical strength of ice very effectively, not by melting it but by going into the grain boundary and decreasing the mechanical strength. You need only 10^{-3} molar lithium chloride or sodium nitrate or some other salts or some organic substances. For instance, 3 ppm of hydrogen fluoride decreases the mechanical strength of ice by one-half. So you need only very small amounts of chemicals to get a weak interface. This has been shown by Smith-Johanssen at General Electric and by Pounder at McGill. You do not need to put tons of inorganic chemicals on the road to melt the ice. Very small amounts make the interface weak, and then it can be pushed off very easily.

Ice Adhesion Studies:
Properties of Defects in the Interfacial Region

S. F. Ackley and K. Itagaki

Considerable work has been done on the surface chemical aspects of ice adhesion. Another point of view, however, is that ice adhesion may be primarily a function of the strength of ice in the interfacial region; i.e., ice sheared from a surface breaks away cohesively in the ice rather than adhesively at the substrate. The properties of ice in the interfacial region, especially those factors that influence the strength of ice (point and line defects), have been investigated this past year. Investigations, including Berg-Barrett and Lang X-ray topography, have revealed line defects in ice to be charged. The presence of this charge is considered in the devising of methods to weaken ice in this region. Other studies include surface self-diffusion, effects of ice-weakening impurities such as hydrofluoric acid, and microhardness investigations to determine the effects on ice dislocation mobility after the use of ice-release agents.

Ice, the most common form of water in the cold regions, has the peculiar property of adhering to almost any substance and, consequently, causing a large variety of problems. Examples include icing on airplane wings causing loss of lift, icing on telephone and power lines causing interruption of services (Fig. 1), and frozen sea spray on the upper structure of a small boat causing it to capsize. Icing on windshields, freezedown of vehicles, engine ice formation, and many other ice formations are all problems of great practical and tactical importance.

There are many secondary factors, such as impurities or irregularities of the surface, that greatly affect the practical problem of ice adhesion and sometimes completely conceal the fundamental mechanism of adhesion. Our approach to the ice adhesion problem is twofold: (a) to obtain fundamental information on those adhesion mechanisms and processes understandable by using solid-state physics, and (b) to find practical and long-lasting methods of ice adhesion control.

In this treatment of the ice adhesion problem, our attention has been not on the actual interfacial bonding process but rather on the forces and mechanical actions that seem to have the preponderant influence in practical situations when the attempt is made to remove ice from a substrate.

The first consideration to be applied is, in essence, a practical one. By looking at the structure of certain materials and water, we can draw conclusions concerning their attraction for one another. Depending on the chemical structure of this substrate material, various interactions with water molecules can be postulated such as hydrogen bonding, dipole-dipole, electrostatic, electrical double layer effects, induced dipole-induced dipole, London dispersion, and van der Waal's forces. The degree of interaction can be characterized by the relative ability of water to spread on a surface; i.e., water will completely wet those surfaces with high interactions and will bead on surfaces with lower interactions. However, certain things became evident in this forest of views. The first point is that even though some substances, such as Teflon, are extremely hydrophobic, that is, they completely repel water, they still require a definite and, in some cases, considerable force to remove ice formed on their surfaces (1). So water repellency does not imply ice phobicity. Therefore, problems in ice adhesion require a somewhat complex and multidisciplinary approach.

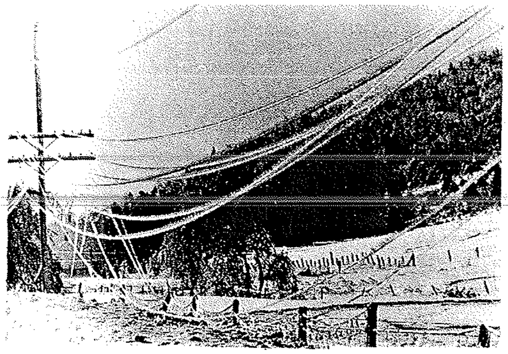

Figure 1. Downed power and telephone lines near Bradford, Vt., caused by ice loading.

As shown by Anderson, (2) Hoekstra (3), and Murrmann (4), the properties of surface adsorbed water are considerably different from that of either bulk water or bulk ice. We also know that on the molecular scale it is extremely difficult to keep things clean so that at the interface there are definite impurity actions that further complicate the attractive interactions of the bonding process. Therefore, with regard to the ice adhesion problem, the interaction of the surface adsorbed layers with the bulk ice and bulk substrate will be very important. There are other views, however, and certain points about this interaction that need clarification.

The first question is that of the process that occurs when ice is removed. In most cases the position of the break is such that the surface adsorbed water remains on the substrate. This situation arises because of the tightly bound nature of this water, which requires very high temperatures along with a quite high vacuum to remove it (5). This nature of surface water is also shown by its attraction for surfaces. For example, to use low energy electron diffraction (LEED), which is a method of looking at the structure of metal surfaces, requires a quite clean surface. Generally, a surface cleaned under a vacuum of 10^{-10} torr is necessary. Even under these conditions, water vapor leached from the vacuum system will absorb on the metal surface and make measurements impossible after only about one hour of operation (6). Evidence by Zisman and Bernett (7) on contact angle measurements on metals and metal oxides indicated that complete monolayers of adsorbed water formed on these surfaces in conditions down to 0.6 percent relative humidity. Therefore, to look at ice adhesion requires that the zone of interest be clearly defined. More confusion will probably be added by the definitions given in Table 1, but they summarize the view taken here and are compatible with those posed by Murrmann. Our contention is that these types of break occur and that they occur predominantly in either Zone 3 or Zone 1 (28). There is no evidence to indicate that the separation of ice from an interface can remove these last few layers of adsorbed water. The structure of this interface will influence and control the defect structure of the ice in Zone 3, but in the study of ice adhesion our prime area of consideration has been the structure of this highly defective ice where we believe most breaks occur. To define the influence that the interfacial layers have on this break zone of highly defective ice, we must know the characteristic defect structures in this zone.

MECHANICAL INTERACTIONS INFLUENCING ICE ADHESIVE STRENGTH

Several theories have developed regarding the strength of adhesive bonds, but the object here will be to speak of only those ideas that pose causes for ice adhesion or a way of reducing it by purely mechanical means, either at the interface or in the bulk of

TABLE 1

ZONES AND TYPES OF BREAKS

Zone	Definition	Type of Break
1	Bulk substrate material	Failure of Zone 1, i.e., the bulk substrate, whether an oil or low shear strength solid
2	Interfacial adsorbed water	Interfacial breaks leaving a clean substrate with no adsorbed water
3	Highly defective ice	Breaks within the highly defective ice

ice. Others have outlined these purely mechanical interactions that influence ice adhesive strength, and they will be briefly reviewed.

Expansion Effects

It has been shown by Bascom et al. (1) that roughing the surface of a substrate can increase the ability of ice to adhere to that surface. Presumably small valleys in the surface trap droplets of water that, upon freezing, expand their volume and push apart the sides of the depression that in turn grip the frozen droplet (8).

There is also a surface roughness effect in the shear-type testing that has been used to measure ice adhesion in the past (8, 9). Mass transfer is required for a deformation to follow the surface profile along the direction of stress. The adhesive strength measured by this shear stress would depend on whether the loading rate allowed plastic deformation to follow the surface profile or whether the shear proceeded by a series of microfractures. Therefore, the surface roughness may cause a high sensitivity of the adhesive strength to the loading rate.

Orientational Effects

Ice deforms plastically much more easily if sheared parallel to the basal plane than in any other direction. Plastic materials have sometimes shown a propensity toward orienting ice crystals preferentially so that the majority of the grains can slip easily in shear (1). Therefore, a careful check of orientation should be made in ice release experiments because orientation effects arise not only from the nature of the substrate but also from the growth habit of the samples. That is, the cooling rate or the way that heat is carried away from the interface can strongly influence the growth habit and the preferred orientation of the grains, which in turn will influence the mechanical strength of the bond, especially if the break obviously occurs cohesionally within the ice.

Mechanical Deformation of the Substrate

Fracture occurs in the substrate material that is either a grease or an oil or a low shear strength crystalline solid such as graphite (9).

Air Entrapment at the Interface

A consequence of the freezing process and of the influence of the substrate material may be that air present when water freezes on the substrate is not driven out as the freezing front moves from the interface but instead is entrapped at or near the interfacial region. This type of ice is considerably weaker at the interface than bubble-free ice and, as a consequence, fracture is initiated more easily in this area and the ice is more easily removed (1).

Impurity Concentrations

Pounder (10) has described this procedure whereby impurities pass preferentially into crystal grain boundaries within the ice, widen them, and thereby weaken the ice structure. Very small amounts (ppm range) of the impurity hydrofluoric acid also have the ability to have the strength of ice as shown recently by Jones and Glen (11). Apparently the cause is quite different from the effect of relatively higher concentration of impurities described earlier and is more intimately related to the dislocation factors described later.

Impurity Effects on Fracture Properties

Impurities can affect not only the strength of ice but also the fracture and plastic properties, areas that have not been studied until quite recently. Nakamura (29) has taken ice bars dipped in HF and drawn them into points similar to molten glass or tied them in bows just with hand pressure. Itagaki and Sabourin (12) in charpy testing (impact hammer) on doped ice crystals found that certain impurities changed the mode of fracture so that the sample shattered into 5 or 6 small pieces unlike the 2- or 3- piece fractures normally seen. Fracture behavior has generally not been closely studied but is an area of great importance for ice adhesion studies because it is more intimately related to the way ice is removed in practical situations.

Defect Processes in the "Thick" Transition Zone

This area has previously been described as a liquid-like layer by Jellinek (13) and others (8). However, our philosophy is to think of this region as a solid with a high concentration of certain types of defects with definite properties associated with defects in a solid as opposed to a liquid. At the temperature considered the solid processes are certainly highly mobile, but it is still verified by our X-ray topography and diffusion studies that the properties of the thick zone are better described by the order more typical of solids than of liquids.

Our particular interest has been in a certain type of defect known as a dislocation. A dislocation is a line defect within a crystal and, simply described, is the absence of a row of atoms over quite a long distance compared with the spacing between individual atoms. Dislocations reduce the shear strength of ice by a factor of about 10^5 compared with ice that contains no dislocations. These defects can also increase the strength of certain materials if tremendous numbers or networks are introduced into the material and they become locked or immobile by interactions between the defects themselves. This network introduction has been used for thousands of years to strengthen metals and is the well-known cold-working or work-hardening procedure. However, the reasons that this process worked have only been understood since the advent of dislocation theory a few years ago. Dislocation structure can also influence fracture properties by concentrating stress at certain points or causing stress relief in preferred directions when a fracture is initiated (14).

The actual measured adhesive strength appears as the weakest link of many mechanisms and cannot consistently be attributed to one mechanism.

RESULTS AND DISCUSSION

Studies on Interface Structure

X-Ray Topography Study—Two techniques are being employed to study dislocation structure in the interface layer. Figure 2 shows a Lang X-ray topograph of ice near an interface. The dislocations appear as dark lines in this topograph. A thin slab of ice was frozen onto a support. The very heavy concentration near the interface layer indicates that the ice is heavily deformed by freezing. The dislocation structure in the interface layer could not be revealed by this topograph because the density is too high, but the strain introduced by the freezing process is evident.

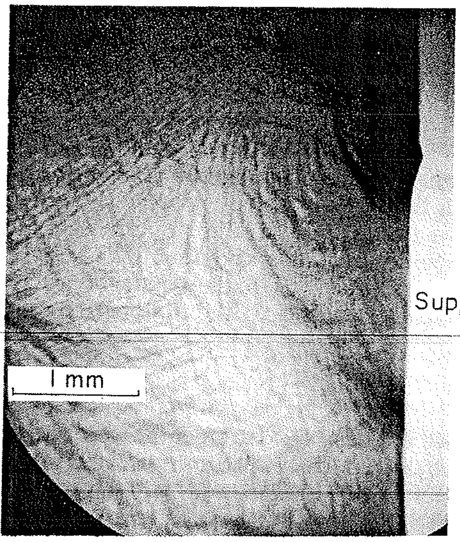

Figure 2. Lang topograph showing dislocations introduced by freezing.

Dislocations were found to be electrically charged because the dislocations can be swept by an electric (ac) field between their pinning points and vibrate as shown in Figure 3 (T = -10 C). The sign is positive and the line is highly charged ($^1\!/_3$ elementary charge per latice spacing). Charged dislocation motion could be a major mechanism of the dielectric relaxation and constant, unlike the previous theory based on the Bjerrum point defect (15). A high density of charged dislocations in the interface layer may produce additional attractive forces due to the

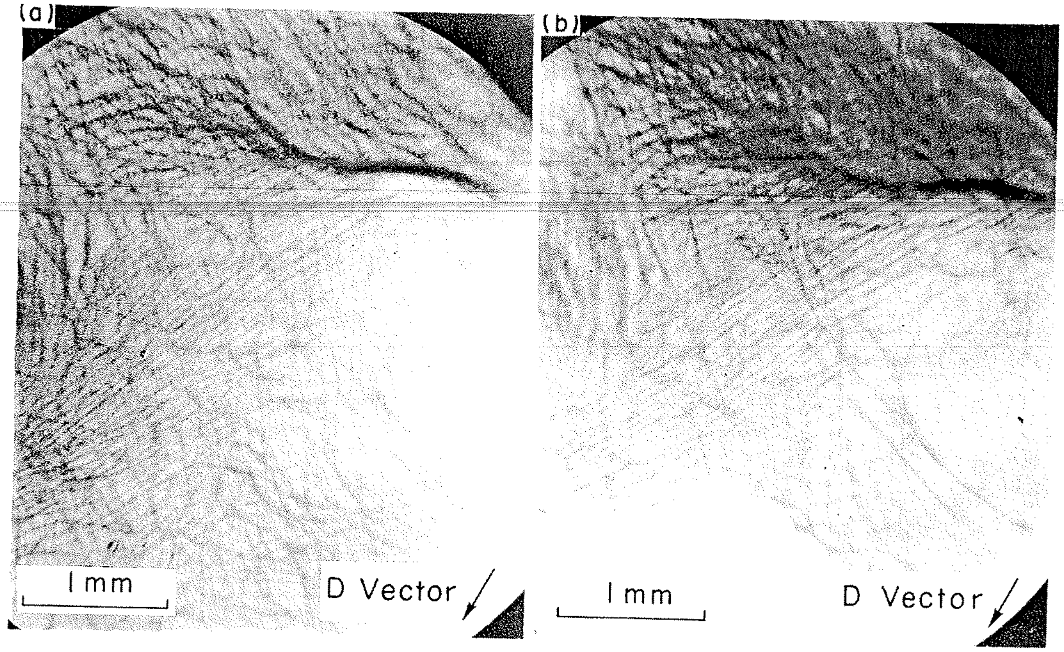

Figure 3. Dislocation structure in a single ice crystal: (a) without electric field and (b) with field, 320 V/cm, 1⅓ Hz.

surface charges and provide another contributory mechanism to ice adhesion.

The Berg-Barrett method is another X-ray topography technique that is more suitable to studies of the near surface layer. Studies are in progress to reveal the dislocation structure in the interface region by freezing the ice onto a substrate and then reducing the ice thickness by successive sublimation. This method should separate out the bulk and near interface ice defect structures and make comparisons possible.

Dielectric Study—Because the dislocations in ice are electrically charged, their motion can be detected by dielectric measurement. Theory predicted that the initial stage of straining would increase the dielectric constant, loss, and relaxation time by unpinning of the dislocation line. In higher straining the segment length becomes shorter because of the dislocation intersection and thus reduces the values disproportionately because the dielectric constant is proportional to the square of segment length while loss depends on the fourth power of segment length. The measured results indicate that the theory is generally correct though simplification in the theory has caused some discrepancy (16) (Fig. 4).

Charged dislocations can also help explain electromechanical interactions observed in ice such as extrinsic piezoelectricity (17, 18) and charge generation (19).

Mass Transfer Along the Interface—Mass transfer in the interface not only is a controlling factor of dislocation motion but also contributes to the macroscopic process of ice adhesion in the effect of surface roughness as pointed out previously. Mass transfer is also an important mechanism in the adhesion of snow and ice particles (sintering) because it can change the contact area and neck size between these particles (20).

The values of self-diffusion in bulk ice seem pretty well established (21, 22, 23, 24), although there are problems in interpreting the mechanism. No published surface mass transfer values are available yet. We have conducted 2 types of measurements, and the results will be published in the near future.

Four mechanisms can contribute to mass transfer along a surface. Surface self-diffusion is a mass transfer mechanism restricted to molecular migration along the surface without penetrating into the bulk. Mass transfer can also proceed through the bulk material when initiated from the surface and terminated onto a different part of

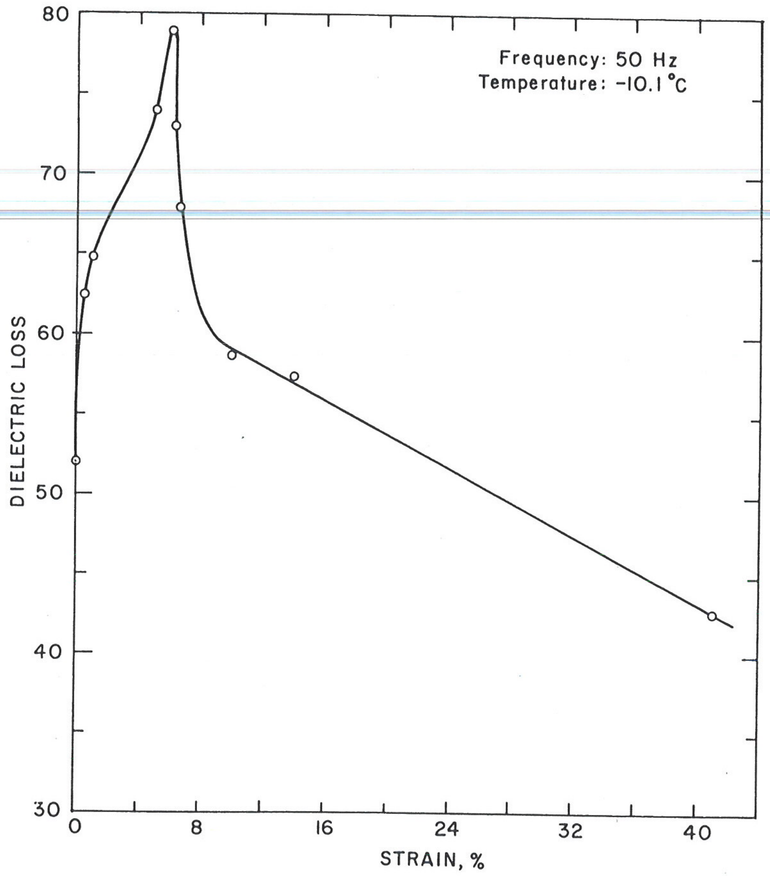

Figure 4. Dielectric loss versus strain in an ice single crystal.

the surface. If the surface of the ice is exposed to the atmosphere, a similar process can proceed as evaporation from the surface, diffusion through the atmosphere, and deposition onto another part of the surface. The fourth mechanism appears when the surface is curved. If a viscous layer covers the ice surface, flow will be initiated by the pressure difference caused by the curvature (25). The 2 independent measurements employed make it possible to distinguish among these mechanisms and assess the contribution from each mechanism. The 2 measurements are as follows:

1. Decay of strain-freely produced grooves. A system of sinusoidal grooves formed on a solid surface will decay or flatten according to the following equation (25):

$$A\omega^4 + B\omega^3 + B'\omega^3 + C\omega = K \tag{1}$$

where $\omega = 2\pi/\lambda$ (ω is the frequency and λ is the wavelength of the periodic grooves); A, B, B′, and C are constants related to the surface diffusion, volume diffusion, diffusion through the atmosphere, and viscosity respectively; and K is the decay constant. A close study of the frequency dependence, ω, can reveal the contribution of each mechanism. However, a determination of the surface diffusion constant, A, is very difficult by this method because of the high contribution of the other mechanisms in the temperature and wavelength range of the experiment. Thus, a radioactive tracer method was required to separate the mechanisms.

2. Radioactive tracer method. Preliminary experiments gave scattered values presumably due to the surface defects introduced during the sample preparation. A method to produce strain-free flat surfaces on ice is essential to use this method properly. This new technique was recently established by our group and will be adapted to the tracer measurement.

A comparison of the groove decay results with the results of the preliminary tracer method show that the surface self-diffusion contribution (A in Eq. 1) is not appreciable in the temperature and wavelength range measured. Instead, the viscous flow term is the major mechanism, and diffusion through the atmosphere can contribute a smaller but comparable amount for groove wavelengths longer than 16 μm. More detailed studies are in progress.

Impurity Diffusion—Certain types of impurities such as hydrofluoric acid are known to soften ice crystals drastically. The effect appears very rapidly (11). A detailed study of HF diffusion suggested that its major mechanism is diffusion along the dislocation core. The higher concentration in the dislocation core can make the dislocation motion easier either by melting the core region and making a liquid core or by producing Bjerrum defects that reduce the resistance of dislocation motion through the solid.

There appears to be some hope to control the adhesive strength by introducing hydrofluoric acid in the interface region.

Breath Figure Study—The controlling factor of ice adhesion in some cases may be more macroscopic than molecular. A trace where ice was frozen on a substrate was observed by blowing warm breath onto the substrate after the ice was removed. Close microscopic study indicated that the fog on the undisturbed surface consisted of a relatively small number of uniform size droplets, while on the surface from where ice was removed the fog produced a larger number of droplets with a greater size distribution. This trace was very stable and remained for a few days. It can be washed away only by using a strong detergent and wiping with considerable force.

This fact may have indicated that the ice made contact with the substrate through the impurity layer at points where the droplets were formed. The adhesive force at the points where the droplets were formed can be stronger than at the other points that were covered by the impurities and may have contributed a greater amount to the total adhesion.

Practical Methods of Adhesion Control

The maximum adhesive strength can be determined as the weakest of the following parts: ice, substrate, or interface, while the van der Waals force limits the minimum between 2 solids. This minimum can be reduced to near zero if liquid exists in the interface and the rate of deformation is very slow.

Liquid Replenishing Lubricant—A layer of oil has been used to reduce the adhesive strength. The major disadvantage of this coating is its short life. Each ice separation reduces the oil thickness by half, which means about $1/1,000$ of the original coating thickness remains after 10 separations. One possible improvement is a water-repellent coating with a replenishing oil layer diffusing out to the surface. Some effort to synthesize this compound is in progress.

Solid Lubricant—There are some indications that a solid lubricant can reduce the adhesive force when the shear force is applied parallel to the interface. Abele and Parrott (26) noticed that snow adhesion onto vehicle tracks can be reduced by the application of flat black paint. One possible explanation of this finding is that the paint contains graphite as a pigment that serves as a lubricant. If this notion is correct, molybdenum disulfide can be a better ice release coating; the experiment is in preparation although preliminary indications have not shown a significant improvement.

Self-Straining Interface—Bascom et al. (1) observed straining in a freshly frozen ice substrate interface layer that later relaxed by recrystallization. Self-induced stress in the freshly frozen interface layer can reduce the external force required to fracture this layer. Certain substrate materials may reduce the adhesive strength by this mechanism and will be revealed by a better understanding of the defect process in this zone.

Application of Certain Types of Energy—The methods described are passive methods and are limited by the van der Waals force if no liquid exists in the interface (27). The

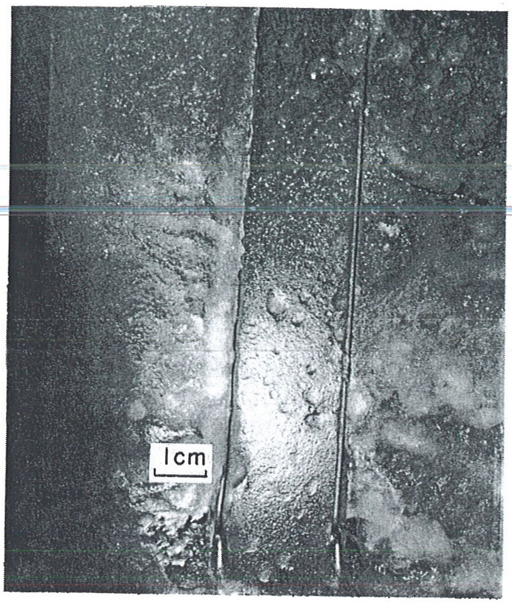

Figure 5. Glaze formed between parallel electrodes.

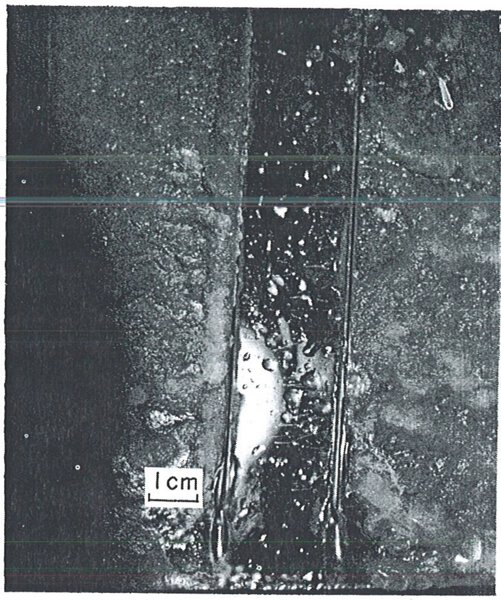

Figure 6. Glaze removed between electrodes after application of 9,000 V/in. ac for approximately 5 sec.

large dielectric constant of ice makes the contribution of the van der Waals force even larger, while rapid mass transfer along the surface of ice makes a fast forming, extensive contact area and reduces the distance between the ice and substrate to the range necessary for van der Waals forces to act.

To overcome this limit may require some energy to initiate a minimum separation. The simplest method seems to be the application of mechanical force. However, the standard laboratory adhesion test using the tensile or shear mode attempts to obtain the maximum force, while practical procedures generally are a peeling or fracture method that requires considerably smaller effort. A more practical and reliable testing method is currently being searched for.

The thermal method is the other method widely used to remove ice. Its efficiency depends highly on the method of delivering the energy. Producing the heat directly in the interface layer will obviously be the best method. Electrical heating can concentrate the heat production in the interface if the substrate is an insulator. The application of sufficient ac voltage to a parallel electrode system can also produce heat in the interface layer. The voltage depends on the conductance in the layer and can be 9,000 V/in. for pure ice down to the order of 10 V/in. if the surface is salted. Unlike indirect heating, this system will turn off automatically when the surface is dry. An example is shown in Figures 5 and 6. A lucite plate that has one set of parallel electrodes was glazed by ice (Fig. 5). The layer of pure ice between the electrodes was melted and evaporated by an electric discharge of 9,000 V/in. ac in about 5 seconds. After the surface was dried no discharge occurred (Fig. 6).

Other possible methods such as infrared or radar are variations of the thermal method with a different procedure of energy delivery and can be classified either by introducing a liquid layer in the interface or by completely removing the ice by melting.

CONCLUSIONS

The problem of ice adhesion includes various aspects, and quick easy conclusions cannot be reached yet. Certain mechanisms may control one case while other mechanisms may become the controlling factor in another case. The data accumulated to date seem too ambiguous to build a solid theory. Method of testing, surface treatment, effect of roughness, impurity layer on the surface, structure of defects—none is treated seriously in previous studies though all of them can affect ice adhesion. More careful studies are in preparation.

The only moderately successful way to reduce ice adhesion to date is to prevent the direct contact of ice with the substrate by a liquid lubricant. Some results obtained using high polymers indicate that low adhesive force may also be attributed to the impurity layer that shows more or less liquid properties. The main disadvantage of the liquid lubricant is its short life. A replenishing lubricant coating will, it is hoped, extend the life to a practical usable range. Other types of coating and treatment also have to be studied more carefully in the light of their influence on interface layer strength.

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Informal Discussion

R. P. Murrmann

How did you obtain the photographs of the ice-aluminum interface?

Ackley

The Lang technique is transmission, and a very thin slab of ice, $^1/_{10}$ mm or so, is gapped into this picture.

Murrmann

Is there any possibility that, when you prepared this, strain was introduced at the interface rather than by the freezing process?

Ackley

It was prepared by slightly warming the interface and letting it refreeze, so the volume change obviously introduces a strain. There was a possibility of mechanical strain being introduced also. We are refining the technique, but I do not think that the handling has been sufficient to account for the number of dislocations we have seen.

William F. Limpert

In your radioactive interface studies, did you ever run a test using sodium-22 below the eutectic point of sodium chloride-water?

Ackley

The tracer diffusion method we used was not ionic. We used a self-diffusion method—tagged water molecules. There is an experiment going on now under the direction of Dr. Weeks at USACRREL that involves freezing salt-ice, using very high concentrations, and modeling sea ice.

H. H. G. Jellinek

We did some work on sodium-22, but with diffusion into polycrystalline ice above the eutectic point. Above the eutectic point the grain boundaries are liquid—a saline solution—and below it they are solid, so the grain boundaries are influenced by temperature.

Limpert

Can you tell whether there is a liquid-like layer at the grain boundaries?

Jellinek

We have not done surface diffusion experiments. We have done diffusion through polycrystalline ice. Once you have attacked the grain boundaries, they would be liquid above the eutectic and solid below. So the diffusion coefficient at the eutectic point should not change suddenly to a lower value.

Compaction or Removal of Wet Snow by Traffic

P. A. Schaerer

Observations were made of the free-water content of snow on roads and its behavior under traffic. A Tapley decelerometer was used to measure the skid resistance of the snow-covered roads. It was found that snow having a free-water content of less than 15 percent was compacted by traffic and formed a slippery surface on which a deceleration value of 0.30 was measured. Snow with a free-water content between 15 and 30 percent was usually not compacted but remained on the road in a soft, loose state and gave deceleration values of 0.35 to 0.42. The exact behavior depended on other variables such as depth, shape, and size of the grains. Snow with a free-water content of 30 percent was removed by traffic. Deceleration values between 0.40 and 0.50 were measured on this surface, and a value of 0.60 was measured on the bare, wet pavement. The observations confirm that chemicals need to be applied only in an amount sufficient to produce 30 percent melting if a decrease of the skid resistance can be tolerated. A melting of 15 percent would prevent the snow from being compacted into an ice crust but usually would not cause it to be removed by traffic, and thus plowing would be required.

Wet snow deposited on a road and exposed to traffic will either be compacted into a hard and slippery snow-ice layer, remain on the pavement in a loose state, or be removed to the side by the action of vehicles. The condition that develops depends on the properties of the snow and characteristics of the traffic. In 1966, the Division of Building Research of the National Research Council of Canada began to obtain information on whether the snow is compacted, remains loose, or is removed. Observations were made on city streets in Ottawa during one winter, and limited observations were carried out in the following years at Rogers Pass, British Columbia. It was not possible, however, to continue the program in its full extent or to bring it to a stage where final conclusions could be drawn. This paper contains preliminary results only.

Pure snow can contain water in liquid form only if its temperature is 0 C. This water may be formed on the snow as it falls through the atmosphere or it may result from rain or from the partial melting of snow on the road. Snow can also be melted partially by the application of chemicals, and in this case the liquid is a solution. Wet snow that contains chemicals in solution can have a temperature lower than 0 C and is the type of wet snow most frequently observed on roads.

OBSERVATIONS OF SNOW CONDITIONS

There are, on the average at Ottawa, 60 days per winter with snowfalls more than 0.25 cm, and on 5 days the amount of new snow exceeds 10 cm. Plowing during snowfalls usually ensures that snow on roads does not accumulate deeper than 7 cm. The principal observation made during and immediately following snowfalls, either before or after plowing, was to classify visually the state of the snow on the road surface by using the following criteria:

1. Compact snow—Pavement is covered with a sheet of dense snow that does not break or move under the action of the traffic;
2. Loose snow—There is no apparent bond between the snow and the pavement, and the snow is broken into chunks or is a cohesionless mass that moves under the wheels of passing vehicles but is not thrown to the side of the road; and

3. Loose snow removed—The wheels of moving vehicles throw the snow to the side, and loose snow from the road accumulates on the shoulder.

The properties of snow that were measured were free water content, depth, density, temperature, and type of crystals.

Free-water content, F, was determined as the weight of the liquid divided by the total weight (liquid plus solid), expressed in percent.

$$F = 100 \frac{W}{W + 1}$$

where

W = weight of liquid (pure water or brine) and
I = weight of ice.

The hot water calorimeter was found to be the most convenient instrument for measuring the free-water content. Because there were significant variations in the free-water content over small distances, it was sometimes necessary to collect in a bucket about 5,000 grams of snow from different spots, mix it, and draw from it 2 to 3 small samples of about 300 grams and melt them in the calorimeter.

The free-water content is the variable that has the strongest influence on the condition of snow on the road. Its effect is discussed in a separate section.

Snow depth on the road was measured by ruler at 10 points selected at random. All observations were made with snow depths between 0.8 and 7 cm. Within this range, depth had no significant influence on whether snow was compacted, remained loose, or was removed by traffic. There appeared to be a change in behavior, however, for very thin layers of snow, 0.2 to 0.5 cm deep.

Layers of this thickness were not removed as readily as snow more than 0.5 cm deep because traffic packed it into the voids of the pavement where it formed a slippery surface. The number of observations on very thin layers, however, was insufficient to draw definite conclusions.

Measurements were made of snow density, but, because density was strongly influenced by the free-water content and varied with location and time, this formation was found to be of little value.

Snow temperature was measured with a shielded glass thermometer. Its value was always consistent with the free-water content, but it appeared to have no direct relation to the behavior of wet snow.

The density of traffic on roads where the observations were made was between 10 and 140 vehicles per hour. Rather than density, the total number of vehicles passing over the snow determined the state of the snow. About one-third of the vehicles were trucks; the reason for this high track ratio is that the observations were made near industrial sites. The speed of traffic was between 30 and 45 km/hr (18 to 27 mph), a normal speed on snow-covered roads in cities.

INFLUENCE OF FREE-WATER CONTENT OF SNOW

Whether wet snow is compacted or removed under the action of traffic depends on the cohesion between the snow grains and their adhesion to the pavement. The study has confirmed that both cohesion and adhesion are strongly influenced by free-water content. Figure 1 shows a plot of observed free-water content against the amount of traffic and the condition of the snow. The values fall into the following 3 zones:

1. Zone A—Initial free-water content less than 15 percent: snow usually compacted on the road;
2. Zone B—Initial free-water content between 15 and 30 percent: snow remains on the the road in a loose condition and is removed by traffic at a slow rate; and

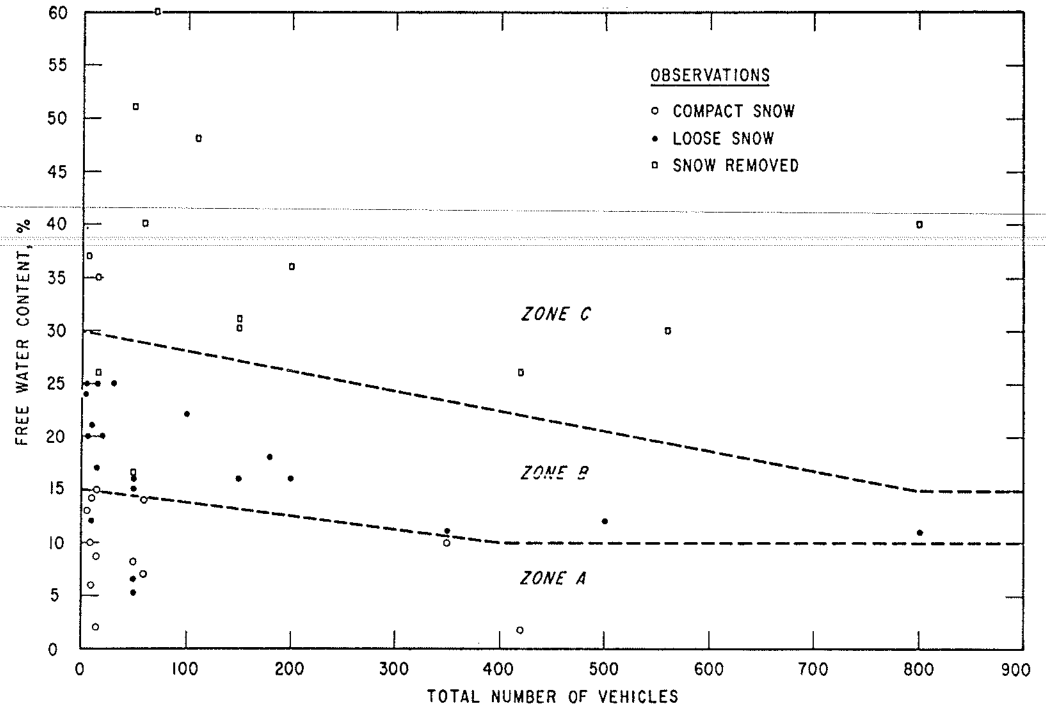

Figure 1. Effect of free-water content and traffic on the compactibility of snow on roads.

3. Zone C—Initial free-water content greater than 30 percent: traffic moves the loose snow to the side rapidly.

The shape of the snow crystals appears to influence the behavior of snow. Rounded grains were moved more readily than needle-shaped or dendritic crystals. This influence is evident only when the snow is fresh. About 2 hours after snow was deposited all the grains had developed a round shape. Zone A in Figure 1 contains observations of snow that was loose and had a free-water content lower than 15 percent. It consisted of graupel and ice pellets.

A similar influence of crystal shape has been reported in measurements of the water-holding capacity of snow. The water-holding capacity is the maximum free-water content that is retained in the snow without producing runoff. de Quervain (1) has observed for dense new snow a water-holding capacity of 20 to 30 percent; for fine-grained old snow, a capacity of 10 to 20 percent; and for coarse old snow, a capacity of 5 to 10 percent. Gerdel (2) reports 13 to 19 percent for new snow and 0.4 to 6 percent for old snow.

The British Road Research Laboratory has recommended for snowfalls the application of 0.0125 lb sodium chloride per inch of new snow, per square yard, per deg F below freezing on roads with a traffic density of more than 50 vehicles per hour, if the resulting wet snow is to be removed by traffic (3). The recommended amount of chemical would produce between 30 and 40 percent melting, which would agree well with the present observations.

OBSERVATIONS OF FRICTION COEFFICIENT

In addition to evaluating the quality of the road surface by observation of the behavior of snow, we took measurements of the friction coefficient. This was determined with a Tapley decelerometer mounted in a light truck driven at a speed of 30 mph

(48 km/hr). Full brakes were applied and the maximum deceleration and corresponding friction coefficient read from the instrument. The results obtained with the Tapley decelerometer are influenced by the type of vehicle and the driver. In order to minimize equipment and human error, the same vehicle and the same operator were used throughout the tests after preliminary experiments had shown that the chosen operator could obtain reproducible results. The Tapley decelerometer, however, was found unsatisfactory for making observations on snow- and ice-covered roads. It was considered that better results could be obtained with a trailer-type, friction-measuring apparatus.

TABLE 1
SUMMARY OF OBSERVED FRICTION COEFFICIENTS

Condition of Snow on the Road	Friction Coefficient (percent)
Compacted wet snow	25-30
Compacted dry snow	30-35
Loose, dry new snow on bare pavement	
1 to 5 cm deep	32-38
5 to 10 cm deep	38-43
Loose, wet snow (free-water content 15 to 30 percent)	
1 to 5 cm deep	
Pavement completely covered	33-38
Center bare 2 ft wide	38-46
Center bare 6 ft wide	44-56
Loose, wet snow on bare pavement (free-water content greater than 30 percent)	42-49
Bare wet pavement	60-70

There is usually a great variation in the friction coefficient of roads having apparently uniform snow conditions, depending on whether one or several wheels of the test vehicle happen to be in direct contact with pavement or ice at the instant the brakes are applied. It was found necessary in the present study to make 8 observations on the same road section in order to obtain a mean value that had a 95 percent confidence limit.

More variables influence the friction coefficient than the degree of compaction of snow on the road. Insufficient observations were made to delineate them and establish their relation to friction. Table 1 gives a general picture of the friction coefficients that were observed. All observations were made on roads with asphalt pavement.

CONCLUSION

Observations of winter road conditions typical of urban areas in eastern Canada indicate that, during light snowfall or after plowing deep snow, chemicals should be applied or pavements should be heated at such a rate that at least 30 percent of the snow is melted. Traffic will move the resulting wet snow to the side of the road. Chemicals should not be applied at a rate that produces less than 15 percent melting, because the resulting wet snow would be compacted into a slippery layer.

It would be useful to continue studies of the friction coefficient of snow- and ice-covered roads in order to determine the influence of different treatments on traffic safety.

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Formal Discussion

S. F. Ackley

Several points are not clear to me in Mr. Schaerer's paper, and elaboration on these points may aid in the evaluation of the data obtained from either an operational or a research viewpoint. There are a number of difficulties in using hot water calorimetry for the 2-component systems encountered on salted roads, and discussion by Mr. Schaerer on how these difficulties were overcome would be appreciated. Specifically, my questions are as follows:

1. Was the specific heat of pure water (1 cal/gm C) or the specific heat of a salt solution (0.88-0.96 cal/gm C, depending on concentration) used in the calculation?
2. Was the melting point of pure ice or a depressed melting point caused by the presence of salt used in the calculation?
3. Because these contributions are salt-concentration dependent, how was the concentration determined to fix the values of the specific heat and depressed melting points?
4. What was the construction of the calorimeter used for these measurements? Specifically, what was the accuracy of the field temperature measurements, and was the mass of hot water used fairly large compared to the sample size?

My purpose in asking these questions is to allow an assessment of the advantages of this system over density measurements for a similar case. Mr. Schaerer has presented numbers for free-water content with an error of about 1 percent (Fig. 1) in his paper. I have done a "worst case" calculation (assuming a specific heat of 0.9 cal/gm C, a melting temperature of -5 C, 500 grams of hot water in the calorimeter at a temperature of 50 C, and a 300-gram sample of snow plus 30 percent free water at -6 C) and have found that, if the factors I have mentioned are completely ignored, an error of 10 percent in the measured free-water content would be quite possible. Although I do not feel that the numbers given by Mr. Schaerer have this large an error, the range possible for error indicated by the calculation is certainly greater than the 1 percent shown, especially in a field situation. A more complete description of the measurement procedure might give a better idea of the accuracy of the numbers presented and allow a more fair comparison with the density method to determine free-water content.

Schaerer

The observations reported in the paper were made at temperatures between -3 and 0 C, and the concentration of chemicals in the wet snow was usually less than 1.5 percent. Tests were carried out in the laboratory at lower temperatures and with higher concentrations of chemicals. Because of the difficulties mentioned by Mr. Ackley, it was decided not to include in the study these extreme conditions.

For all observations made on salted roads, the amount of sodium chloride or calcium chloride was determined in the laboratory with samples of about 500 grams of wet snow. The snow was melted, and the meltwater was filtered and then evaporated in the drying oven. For some samples the concentration of salt was determined by measuring the electrical conductivity of the solution.

The specific heat of the salt solution was used in the calculation of the free-water content. Because of the low concentration of salt, the specific heat was assumed to be 0.98 cal/gm C. The melting point depression due to the presence of chemical was also considered. A correction was also made for impurities of dust, sand, and rock chips usually contained in the snow on roads. These minerals could amount to 3 percent of the snow; a specific heat of 0.25 cal/gm C was assumed for them.

The calorimeter that was found to be best suited was a wide-neck thermos flask, volume 2,000 cm^3, with a cork stopper. It is most important to work always in the same temperature range and with the same amount of water, which must also be used to determine the heat capacity of the calorimeter. The following are the characteristics of the water and mixture used in our measurements:

Temperature of hot water, 35 C
Temperature of mixture after melting, 5 to 10 C
Amount of hot water, 1,000 grams
Amount of snow, 300 to 400 grams

The temperature was measured with a mercury thermometer graduated in 1/10 C. The greatest heat loss and possibility of error occurs when the cork stopper is removed and the snow added to the hot water. With some practice this can be done quickly and the error kept within reasonable limits.

The number of observations that could be carried out on the road was too limited to make an evaluation of the influence of all possible errors. It would appear that the variation in the free-water content of the snow on a road produces a greater error than inaccuracies of the calorimetric measurements. The information presented in the paper should only be taken as an indication of the trend in the relationship between free-water content and the condition of the snow. Additional studies must be carried out before a detailed analysis of the effect of traffic on wet snow can be undertaken.

Informal Discussion

Lorne W. Gold

What was the particle size of the salt, in other words, the screen size used?

Schaerer

We have used sodium chloride that meets the specification of the Ontario Department of Highways. Can you tell us what this is Mr. Brohm?

David Brohm

The salt we normally use for highway work is coarse-crushed, maximum size somewhere around 1/4 in.

Gold

Some European countries use very fine salt, so tests run there would give results that are almost meaningless because there is not a wide range of particle sizes to get down to the interface.

Brohm

Our coarse-crushed salt specification, which is not much different from that commonly used in the United States, does permit a fair amount of fines. It covers a fairly broad band. You cannot really pin it down unless you have an analysis of the salt being used.

M. E. Volz

Apparently there is a great deal of discrimination among definitions of wet snow. Am I correct that your definition is snow with a water content in excess of 30 percent?

Schaerer

Wet snow is any snow that has a certain amount of liquid.

Volz

What amount?

Schaerer

Anything with 1 percent and more.

H. R. Kivisild

I noticed from the graph that traffic intensity has hardly any effect.

Schaerer

The tests were run up to a maximum of 4 hours immediately after snow deposition.

Glenn Balmer

We have made tests with a skid trailer on snow and obtained results very comparable to yours.

Schaerer

Thank you. That is very encouraging.

Skid Resistance of Snow- or Ice-Covered Roads

Kaoru Ichihara and Makoto Mizoguchi

This paper reports skid resistance coefficients obtained on snow- or ice-covered roads. Skid resistance changes according to snow conditions, temperature, kinds of vehicle tires, and chemicals used. Three classifications of skid resistance used are skid resistance in braking condition, skid resistance in driving condition when the tire does not slip and just before it begins to spin, and skid resistance in driving conditions when the tire is spinning. These data are used in discussion of stopping distance, longitudinal gradient, and cross fall of the road.

Under normal conditions, braking force is produced by the friction between road surface and tire. When a snow or ice layer is present on a pavement, we are concerned with the friction between the layer and the tire. The coefficient of friction on a snow- or ice-covered surface is considerably smaller than that on a normal pavement. Because of this low friction, we have many problems, such as longer stopping distances or a limiting longitudinal gradient for a vehicle to start. To solve these problems, we measured and analyzed coefficients of friction on various snow or ice surfaces.

CLASSIFICATION OF COEFFICIENTS OF FRICTION ON SNOW- OR ICE-COVERED ROADS

Usually braking force is measured, and the value obtained is applied to the evaluation of pavements. On snow- or ice-covered pavements, traction force coefficients that define whether vehicles will be able to start from standstill are of as much concern as the braking force coefficients. The braking force coefficient is used not only for calculating stopping distance but also for analyzing the motion of the vehicle in skidding.

When a vehicle starts from a standstill, the traction force increases gradually; but when the tire begins to spin, the traction force drops to a lower value (Fig. 1). This fact leads to complications in the determination of the maximum gradient for starting on snow- or ice-covered surfaces. Furthermore, tire spin can occur not only when the vehicle begins moving but also after the vehicle is in motion.

For these reasons, the authors classified the possible coefficients of friction on snow- or ice-covered roads into 4 categories: braking force coefficient, traction force coefficient of tire immediately before it begins to spin, traction force coefficient of spinning tire with stationary vehicle, and traction force coefficient of spinning tire with moving vehicle.

BRAKING FORCE COEFFICIENT

Skid Resistance Coefficient

Table 1 gives skid resistance coefficients on various snow- or ice-covered roads. On flat ice surfaces, coefficients are around 0.1, sometimes dropping to near zero on completely flat surfaces. On a new snow layer compacted by traffic, coefficients of 0.10 to 0.15 are observed. On a compacted snow or ice surface, which is most frequently observed, coefficients are around 0.2 to 0.3. When a snow layer becomes relatively old and its surface has changed into relatively large ice granules (through melting and freezing processes), coefficients of friction are in the range of 0.3 to 0.5.

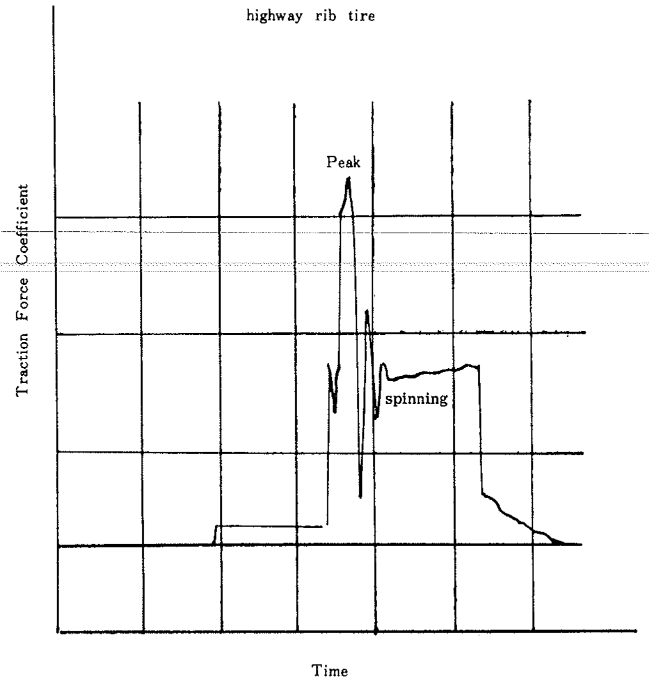


Figure 1. Change of traction force coefficient at starting time.

In this case, the crushing resistance of this old snow layer is included. When sand or small crushed stone or small amounts of chlorides (NaCl, $CaCl_2$, or $MgCl_2$) are spread on snow- or ice-covered roads, coefficients of friction are increased to 0.3 to 0.4. It is obvious that the coefficient of friction increases as snow or ice disappears either by using large amounts of chlorides or by pavement heating.

Slip Resistance Coefficient

Figures 2 and 3 show coefficient of friction under slip on various snow- or ice-covered roads. Generally on a wet

TABLE 1

SKID RESISTANCE COEFFICIENTS ON SNOW- OR ICE-COVERED ROADS AT A SPEED OF 30 TO 40 KM/HR

Snow or Ice Condition	Skid Resistance Coefficient
Ice	0.1 to 0.2
New snow	0.2 to 0.25
Old snow	0.25 to 0.30
Refrozen snow	0.30 to 0.40
Chloride-treated snow	0.35 to 0.45
Sand-treated snow	0.30 to 0.40
Chloride-sand mixture	0.30 to 0.50

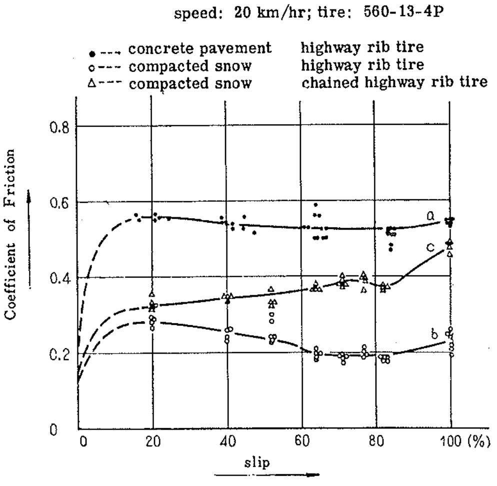
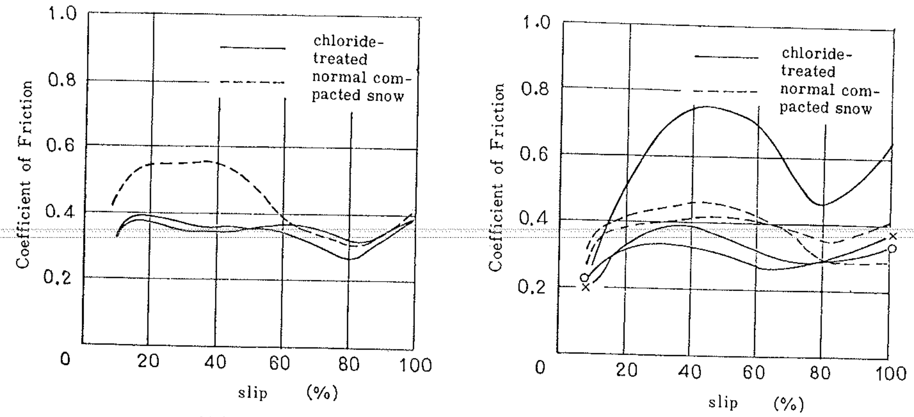
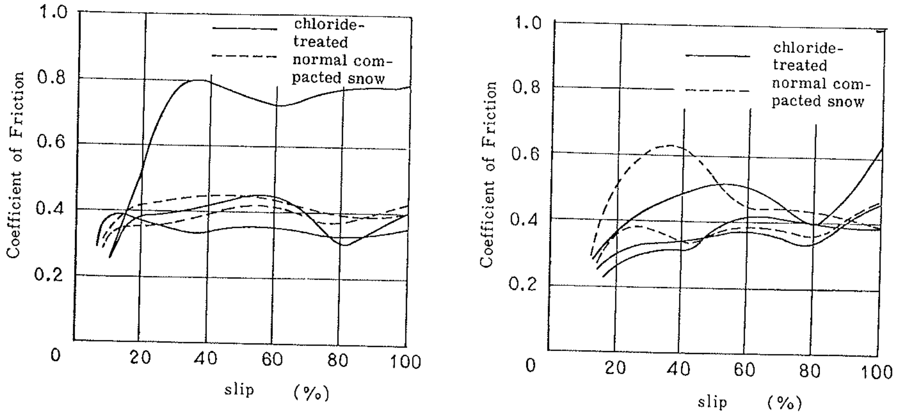


Figure 2. Coefficient of friction under Slip 1, 1967.



highway rib tire

snow tire



studded snow tire

chained highway rib tire

Figure 3. Coefficient of friction under Slip 2, 1968.

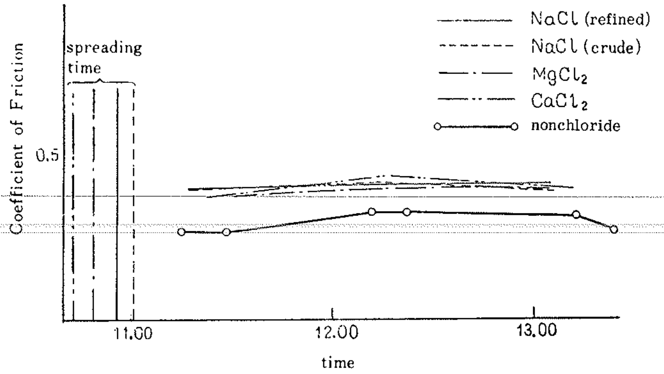
pavement, maximum coefficient of friction occurs around 20 percent slip. On snow- or ice-covered roads, however, maximum values were observed at higher slip, and several patterns were seen according to the type of tire and state of the snow.

Maximum values were observed at 20 to 30 percent slip with highway rib tires, at 40 to 60 percent slip with snow tires or studded snow tires, and at 80 to 100 percent slip with chained highway rib tires. This means that the slip ratio at maximum friction moves toward higher slip according to allowable tread deformation of the tire.

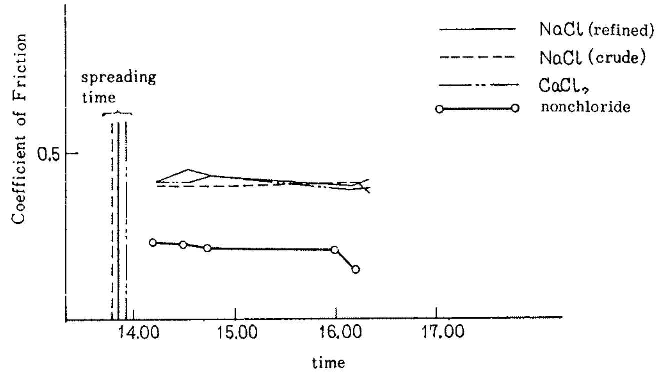
On the other hand, on a normal compacted snow surface maximum values were observed at 20 to 40 percent slip, and at higher slip on a chloride-treated surface. Maximum values occur at relatively low slip on a hard snow surface and at higher slip on a soft snow surface. However, the differences between these maximum values and skid resistance coefficients at 100 percent slip are small.

Effect of Chemicals and Sand

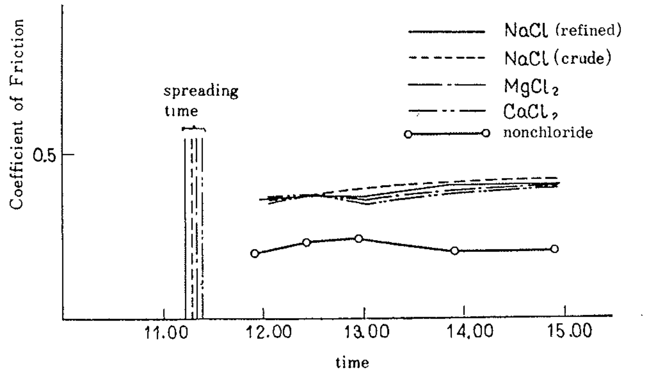
Chloride—Changes of skid resistance on chloride-treated roads are shown in Figure 4. In these cases, 50 g/m^2 of chloride were spread prior to skid measurements. Higher coefficients of friction were observed on treated surfaces. Chlorides improved skid resistance by about 0.05 to 0.15, producing skid resistance values of about 0.4



Morioka



Yamagata



Aomori

Figure 4. Effect of chlorides.

(with snow tires) regardless of original values. No difference among the chlorides was observed.

Sand—Figure 5 shows the effects of sand and sand-chloride mixtures. These tests were conducted by the Civil Engineering Experimental Laboratory, Hokkaido Development Bureau. The effect of sand was relatively small. High coefficients of friction (0.4 for snow tires) were observed with high chloride content. This is considered to be an effect of the chloride itself.

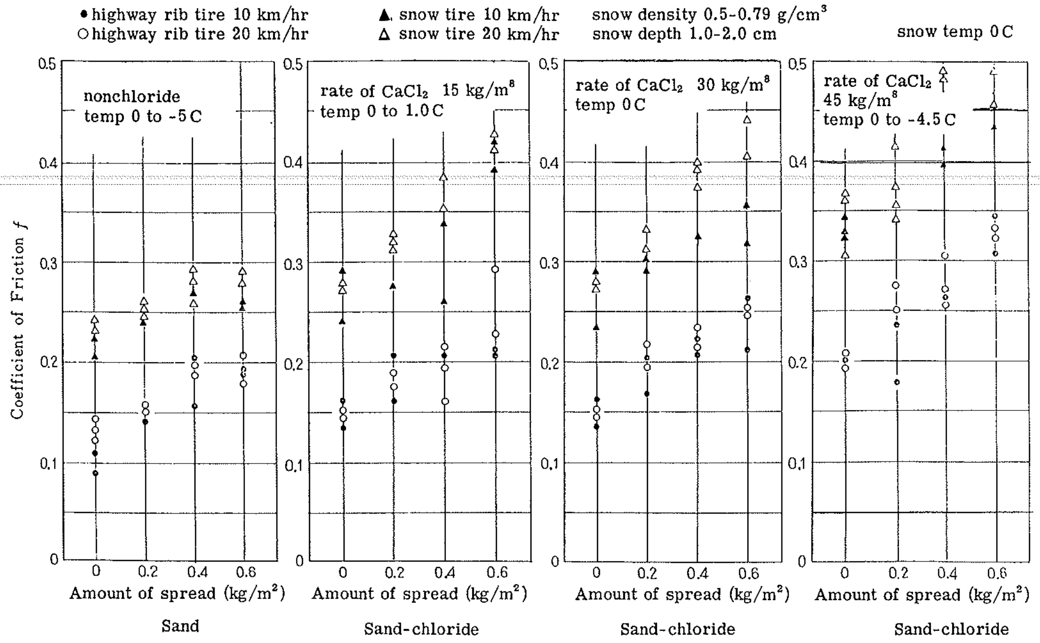


Figure 5. Effects of sand and sand-chloride mixtures.

Effect of Speed and Temperature

Figure 6 shows the relationship between coefficient of friction and speed on snow- or ice-covered roads. Coefficient of friction is low at low speed and does not change much with increasing speed. As speed increases the crushing resistance of the snow layer also increases. These facts are completely different from those for wet skidding.

Skid resistance coefficients on snow- or ice-covered roads were measured at 5 locations in northern Japan during the 1968-1969 winter. Table 2 gives these data tabulated by temperature. Coefficients of friction were observed to be relatively low at temperatures around 0 C and higher at temperatures both above and below the freezing point. But characteristics of skid resistance on snow- or ice-covered roads are not classified by temperature only.

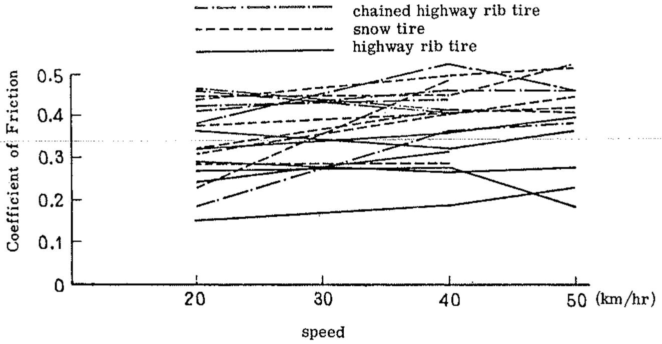


Figure 6. Coefficient of friction and speed.

TABLE 2

TEMPERATURE AND SKID RESISTANCE COEFFICIENTS

Temperature (deg C)	Hokkaido	Tōhoku	Hokuriku	Joetsu	Average
			Highway Rib Tire		
-5					
-5 to 0				0.272 0.392	0.272-0.392 0.332(2)
0 to +2.5					
+2.5 to +5.0					
			Snow Tire		
-5	0.301 0.232				0.232-0.301 0.266(2)
-5 to 0	0.333 0.250 0.290	0.369	0.208 0.399 0.379 0.209	0.261 0.372 0.422	0.208-0.422 0.317(11)
0 to +2.5		0.262 0.328 0.392	0.436 0.917	0.558 0.502	0.197-0.558 0.382(7)
+2.5 to +5.0		0.259 0.211 0.245 0.178 0.439		0.593	0.178-0.593 0.321(6)
			Studded Snow Tire		
-5	0.298 0.260				0.260-0.298 0.279(2)
-5 to 0	0.324 0.335 0.325			0.296	0.296-0.335 0.320(4)
0 to +2.5		0.433 0.439			0.433-0.439 0.436(2)
+2.5 to +5.0					
			Chained Highway Rib Tire		
-5	0.323 0.248				0.248-0.323 0.286(2)
-5 to 0	0.365 0.215 0.340		0.337 0.365 0.317 0.282	0.480	0.215-0.480 0.337(8)
0 to +2.5	0.195	0.217 0.220 0.223 0.202 0.247 0.240 0.280	0.401 0.315		0.195-0.401 0.254(10)
+2.5 to +5.0		0.215 0.204			0.204-0.215 0.210(2)

TABLE 3

TRACTION FORCE COEFFICIENTS AT START AND ROLLING RESISTANCE, 1968

Location	Condition	Waiting Time (sec)	Test Tire							
			Highway Rib Tire		Snow Tire		Studded Snow Tire		Chained Highway Rib Tire	
			Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
Kurikara[a]	Spinning[e]		0.093-0.117	0.106(3)					0.426-0.461	0.444(2)
	Spinning[f]	30	0.119-0.157	0.134(3)					0.405-0.536	0.455(5)
	Spinning[f]	300	0.111-0.152	0.127(3)						
Amada[a]	Spinning[e]		0.040-0.085	0.070(3)	0.039-0.404 0.369-0.432	0.322(2) 0.400(2)	0.419-0.440	0.430(2)		
	Spinning[f]	30	0.064-0.086	0.070(4)	0.145-0.204 0.258-0.377	0.184(3) 0.324(3)	0.558-0.678	0.617(3)		
Amada[b]	Spinning[e]		0.337-0.365	0.349(3)	0.309-0.506	0.396(3)	0.361-0.453	0.398(3)	0.452-0.471	0.460(3)
	Spinning[f]	30	0.043-0.187	0.133(3)	0.383-0.517	0.460(4)	0.367-0.481	0.448(4)	0.269-0.418	0.351(3)
	Rolling resistance		0.066-0.089	0.083(4)	0.075-0.108	0.092(8)	0.060-0.101	0.084(6)	0.079-0.113	0.090(5)
Kanazawa Un.[c]	Spinning[e]		0.210-0.240	0.223(3)	0.318	0.318(1)	0.449-0.469	0.459(3)	0.345-0.387	0.370(3)
	Peak value	30	0.166-0.601	0.307(5)	0.507-0.743	0.665(5)	0.713-0.888	0.778(9)	0.689-0.805	0.753(4)
	Spinning[f]	30	0.052-0.221	0.149(5)	0.333-0.593	0.442(5)	0.149-0.645	0.484(9)	0.489-0.563	0.525(4)
	Peak value	120	0.269-0.398	0.334(2)	0.593-0.716	0.662(4)	0.820-0.962	0.872(4)	0.646-0.844	0.747(4)
	Spinning[f]	120	0.097-0.137	0.117(2)	0.194-0.426	0.274(4)	0.429-0.512	0.474(4)	0.453-0.576	0.519(4)
	Rolling resistance		0.043-0.058	0.049(4)	0.0574-0.082	0.069(2)	0.054-0.064	0.603(4)	0.0509-0.0679	0.057(4)
Izumigaoka[c]	Spinning[e]		0.184-0.190	0.188(5)	0.288-0.312	0.306(5)	0.365-0.379	0.373(3)	0.424-0.462	0.445(3)
	Peak value	30	0.209-0.246	0.230(3)	0.372-0.568	0.500(4)	0.543-0.760	0.628(6)	0.626-0.667	0.647(4)
	Spinning[f]	30	0.141-0.205	0.170(3)	0.073-0.153	0.122(4)	0.113-0.212	0.152(6)	0.489-0.531	0.504(4)
	Peak value	120	0.200-0.227	0.209(3)	0.490-0.578	0.537(3)	0.568-0.578	0.573(3)	0.667-0.722	0.698(5)
	Spinning[f]	120	0.108-0.145	0.131(3)	0.148-0.173	0.158(3)	0.103-0.133	0.118(3)	0.489-0.571	0.517(5)
	Rolling resistance		0.031-0.040	0.036(5)	0.039-0.049	0.044(5)	0.061-0.063	0.062(5)	0.049-0.053	0.052(5)
Yuzawa[d]	Spinning[e]		0.118-0.130	0.124(2)	0.289-0.324	0.307(2)	0.262-0.300	0.281(2)	0.307-0.332	0.319(2)
	Peak value	30			0.23-0.26	0.252(5)	0.38-0.48	0.43 (7)	0.347-0.417	0.383(4)
	Spinning[f]	30	0.12-0.16	0.142(5)	0.09-0.15	0.124(5)	0.15-0.28	0.21 (7)	0.301-0.352	0.326(4)
	Peak value	80			0.36-0.42	0.402(5)	0.42-0.48	0.452(5)	0.471-0.501	0.487(5)
	Spinning[f]	300	0.13-0.15	0.14 (5)	0.12-0.18	0.158(5)	0.17-0.31	0.224(5)	0.373-0.358	0.376(5)
	Peak value	300			0.28-0.39	0.357(3)	0.43-0.50	0.462(4)	0.45-0.48	0.460(4)
	Spinning[f]	300	0.12-0.14	0.125(4)	0.14-0.16	0.153(3)	0.18-0.20	0.187(4)	0.32-0.37	0.345(4)
	Rolling resistance		0.026-0.028	0.027(2)	0.035-0.037	0.036(2)	0.035-0.042	0.038(2)	0.031-0.034	0.032(3)
Mitsumata[d]	Spinning[e]		0.10-0.112	0.107(3)	0.10-0.112	0.107(3)	0.08-0.14	0.11 (5)	0.381-0.385	0.383(2)
	Peak value	30	0.21-0.30	0.236(4)	0.21-0.30	0.248(7)	0.36-0.39	0.378(5)		
	Spinning[f]	30	0.10-0.12	0.11 (4)	0.08-0.11	0.09 (7)	0.12-0.17	0.144(5)	0.33-0.37	0.346(5)
	Peak value	60	0.18-0.22	0.196(5)	0.21-0.26	0.232(5)	0.32-0.41	0.356(5)		
	Spinning[f]	60	0.10	0.10 (5)	0.07-0.11	0.09 (5)	0.11-0.15	0.128(5)		
	Rolling resistance		0.20-0.22	0.020(3)	0.019-0.022	0.020(3)	0.015	0.015(3)	0.022-0.025	0.023(3)

[a] Compacted snow on road.
[b] Hard compacted snow on road.
[c] New snow on road.
[d] Normal snow on road.
[e] Vehicle moving.
[f] Vehicle not moving.

Lateral Force Coefficient

Maximum values of lateral force coefficients on snow- or ice-covered roads are about the same or slightly larger than skid resistance values. On a flat ice surface, the maximum lateral force coefficient is approximately equal to the skid resistance coefficient. On a snow layer or a chloride-treated snow surface, however, the maximum lateral force coefficient is higher than the skid resistance coefficient. Probably the effect of crushing resistance of the snow layer increases under sideslip conditions.

TRACTION FORCE COEFFICIENT

The basic idea of traction force coefficient was discussed earlier. Tables 3 and 4 give traction force coefficients under various conditions. Traction force coefficients are influenced by the state of snow or ice on the road and by the type of tire.

Traction Force Coefficient and Type of Tire

A highway rib tire develops its maximum coefficient of 0.17 or more immediately before spinning, but while spinning this drops to around 0.1 (minimum observed was 0.04). On the other hand, the peak value with snow tires is 0.21 or more (normally 0.35 or more), and minimum while spinning is 0.07.

As for peak values, a highway rib tire develops much less traction than the other 3 types of tires, which develop more than 0.35. Differences among these 3 types of tires are small. As for traction force coefficient upon spinning, however, the chained rib tire develops the highest value, followed by the studded snow tire. These high values of the chained tire are considered to be a result of the scratching action of the chain.

Waiting Time and Traction Force Coefficient

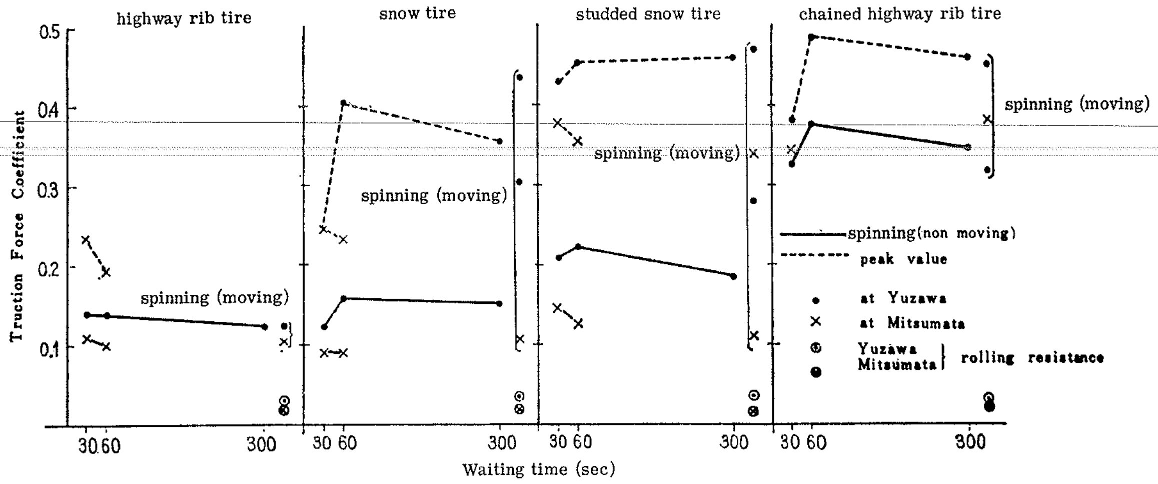
Once we bring a car to a stop on a slippery snow or ice road, we sometimes have difficulty starting it again. To investigate the influence of waiting time on such a surface, the authors measured a change of traction force coefficient due to time elapsed between stopping the vehicle and starting again. Figure 7 shows these results. Little change due to waiting time was seen.

TABLE 4

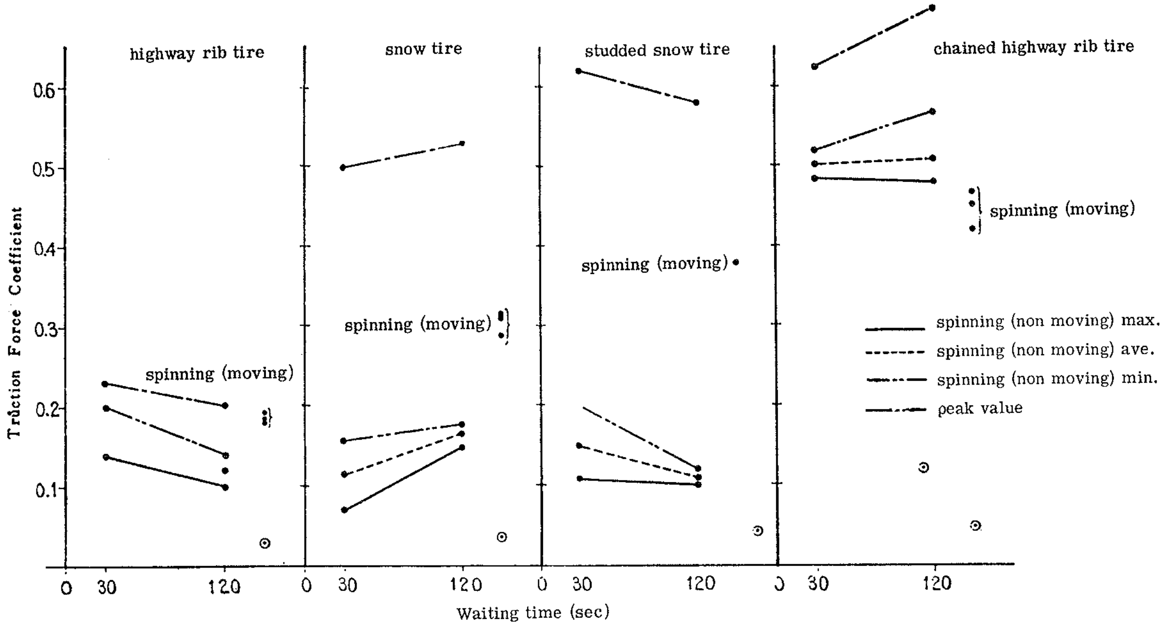
TRACTION FORCE COEFFICIENTS AT START AND ROLLING RESISTANCE, 1969 AT MITSUMATA

Condition	Waiting Time (sec)	Test Tire					
		Highway Rib Tire		Snow Tire		Studded Snow Tire	
		Range	Avg	Range	Avg	Range	Avg
Spinning (nonmoving)	0	0.136 (0.101-0.112)	0.136(3) 0.108(3)	0.126-0.136 (0.167-0.171)	0.130(3) 0.168(3)	0.243-0.298 (0.267-0.324)	0.278(6) 0.301(6)
Peak value	30	0.270-0.369 (0.257-0.302)	0.322(5) 0.307(5)	0.314-0.379 (0.319-0.371)	0.337(5) 0.334(5)	0.550-0.605 (0.497-0.505)	0.571(3) 0.499(3)
Spinning (nonmoving)	30	0.125-0.189 (0.089-0.114)	0.160(5) 0.104(5)	0.140-0.153 (0.121-0.136)	0.148(5) 0.135(5)	0.413-0.443 (0.424-0.438)	0.427(3) 0.428(3)
Peak value	60	0.238-0.311 (0.274-0.333)	0.278(5) 0.307(5)	0.348-0.379 (0.343-0.417)	0.387(3) 0.373(3)	0.547-0.649 (0.497-0.531)	0.598(4) 0.515(4)
Spinning (nonmoving)	60	0.108-0.152 (0.100-0.121)	0.131(5) 0.111(5)	0.136-0.170 (0.129-0.144)	0.150(3) 0.139(3)		
Peak value	300	0.246-0.292 (0.279-0.288)	0.275(3) 0.282(3)	0.373-0.452 (0.367-0.474)	0.406(3) 0.414(3)	0.575-0.633 (0.526-0.538)	0.604(2) 0.532(2)
Spinning (nonmoving)	300	0.112-0.126 (0.101-0.112)	0.119(3) 0.104(3)	0.126-0.143 (0.099-0.150)	0.135(3) 0.121(3)		
Rolling resistance		0.025	0.025(3)	0.022-0.023	0.023(3)	0.022-0.031	0.025(3)

Note: Road temperature was 0 C; road condition was compacted snow; and the temperature was -0.5 to 0 C.



Yuzawa



Kanazawa

Figure 7. Traction force coefficients at start versus waiting time.

TABLE 5

MINIMUM COEFFICIENT OF FRICTION

Type of Tire	Traction Force Coefficient	Skid Resistance Coefficient	Rolling Resistance
Highway rib	0.04 to 0.17	0.15	0.02 (0.05)
Snow	0.07 to 0.21	0.16	0.02
Snow studded	0.08 to 0.27	0.20	0.02
Chained highway rib	0.02 to 0.35	–	0.03

TABLE 6

PERCENT MAXIMUM STARTING GRADIENT

Type of Tire	Passenger Car	Truck	Semitrailer
Highway rib	-0.4 to 4.9 (1.9)	-0.3 to 5.3	-0.5 to 4.1
Snow	0.9 to 6.6	1.0 to 7.0	0.6 to 6.0
Studded snow	1.3 to 9.1	1.4 to 9.6	1.0 to 8.3
Chained highway rib	9.1 to 12.3	9.6 to 13.1	8.3 to 11.3

TRACTION FORCE COEFFICIENT AND MAXIMUM STARTING GRADIENT

Maximum longitudinal gradient of roads, which is influenced by snow or ice, should be determined by gradient at the start. These gradients are calculated by traction force coefficients and resistances at time of starting.

When we take as a distribution coefficient, β, the ratio of driving axle load to full load of vehicle, then the ratio of traction force to full load of this vehicle becomes β times traction force coefficient. Values of β, which are considered conservative for highway design for various vehicles are as follows:

Vehicle	β
Passenger car	0.41
Truck	0.43
Semitrailer	0.38

On the other hand, generalized minimum traction force coefficients on a snow- or ice-covered road are given in Table 5. In this table, lower and higher values correspond to the spinning state and the state immediately before this respectively.

The values of β and Table 5 were used to compute maximum starting gradients. These are shown in Table 6. The lower values correspond to traction force coefficients at spin and are considered the starting gradients for least skilled drivers with the worst snow or ice conditions. The higher values show gradients computed from maximum traction force coefficients immediately before spinning, and only the most skilled drivers can start on these gradients with the worst road condition. Because acceleration resistance is not accounted for in these computations, actual starting gradients might be somewhat lower than the values listed.

When we determine maximum starting gradient for highway design, the decision should be based on the type of tire that would be used.

CONCLUSIONS

Generally, because coefficients of friction on snow- or ice-covered roads are much lower than those on wet pavements, special attention must be given to them. On a snow- or ice-covered road, coefficient of friction varies over a wide range according to snow or ice conditions, type of tire, and driving conditions. Further, considerable difference exists between braking force and traction force coefficients, so it is important to consider these 2 conditions separately.

When we determine geometric design standards for highways that will be influenced by snow or ice, special considerations must be taken, such as maintenance level and the type of tire that will be most used.

Informal Discussion

Glenn G. Balmer

I have done work with the Committee on Winter Driving Hazards of the National Safety Council and I would like to emphasize one point that was made in this paper, that is, the temperature of the ice at the time the skid resistance is measured. The ice is most slippery when it is near the melting point, and the skid resistance increases as the ice becomes colder. At 32 deg on glare ice, you may get a skid resistance value between 0.05 and 0.1. As the temperature gets colder and drops to 0 F, the skid resistance value may increase to 0.2 or 0.25.

J. W. Renahan

What happens if it gets colder?

Balmer

There is a gradual decrease in the skid resistance as the temperature increases up to the melting point of the ice. At temperatures below 0 F, it seems to level out, and there is not too much change in the skid resistance as it gets considerably colder.

Renahan

At fifty below, driving is good.

Balmer

I have never measured the skid resistance at temperatures that low. We have measured it at 0 and about 5 below, and it seems to be leveling out. I do not know too much about it at really cold temperatures.

Renahan

Is there a stage at which your tires stick to the ice?

J. L. Smith

The closer you get to the melting point, then the closer you get to a hydroplaning stage. Is that what it is?

Balmer

Above 32 deg the ice begins to melt on the surface and the water lubricates the remaining ice. That is the reason it becomes very slick. There is another factor that comes into play, and that is the type or texture of the ice. Rough-textured ice is not as slick as glare ice. There are also other factors such as the type of tire you use—highway tires, studded tires, or tires with chains.

Ichihara

I previously showed that the same results were observed in Japan. At the freezing point the friction coefficient is lowest.

William D. Glauz

In the tests where the vehicle was stopped then started later and you measured the change (in friction coefficient), can you say anything about the tire temperatures? Were the tires cold or warm?

Ichihara

We did not measure the tire temperature at that time.

Glauz

Do you think that tire temperature might be important?

Ichihara

I think so. If the tire temperature is high, the snow layer melts between the tire and snow surface, and this contributes to the lower friction coefficient.

Lawerence H. Chenault

Some years ago I did a great deal of work on skid resistance with tires. It might be of interest that the durometer of the tire rubber had a great deal of effect, that is, the softer durometer gave better skid resistance. Tire pressure did not seem to have so great an effect. Tire tread pattern was a very great factor.

Effect of Salt on Reinforced Concrete Highway Bridges and Pavements

J. N. Hall and S. P. LaHue
(presented by P. E. Cunningham)

The deterioration of bridge deck concrete has caused serious concern among highway engineers for several years. Considerable research has been undertaken to determine the causes for this deterioration. It is generally agreed that surface spalling is the most serious and annoying type of distress found in bridge decks. Several recent research reports indicate that corrosion of reinforcing steel is often a factor in the occurrence of surface spalls. This paper focuses on this relationship and discusses the various factors that may contribute to corrosion of reinforcement.

Maintenance reports, research studies, and field inspections indicate that bridge deck durability is a serious problem in almost all states. Premature deck deterioration has been reported with sufficient frequency to warrant modifications that will prevent or minimize such problems in the future.

The Portland Cement Association, Highway Research Board, several state highway departments (Fig. 1), and other agencies have conducted research to identify the types

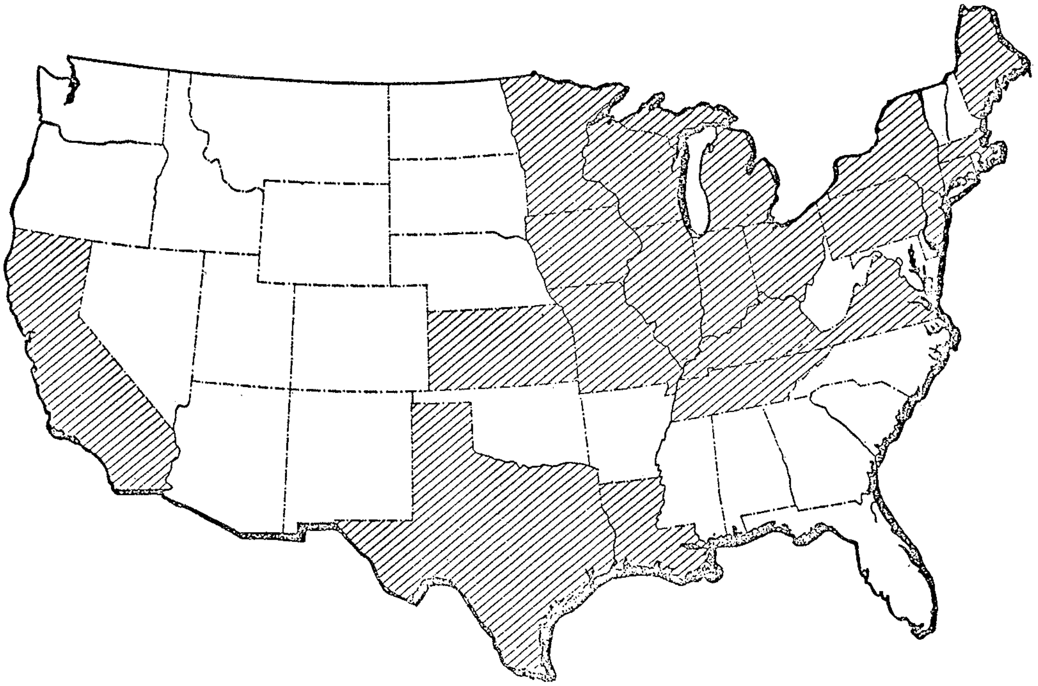


Figure 1. States that have conducted research on bridge deck durability.

and causes of deterioration. As a result, we are beginning to identify present problems and make changes that will provide structures with longer service lives.

For instance, concrete scaling has long been a recognized problem. Many states now report that scaling of bridge decks is not a serious problem although some surface scaling still occurs. This success has been attributed to the superior freeze-thaw resistance of air-entrained concrete. In addition, waterproofing systems have made a contribution, especially to poor quality of non air-entrained concrete.

Recently, several reports identified concrete spalling as the most serious form of deck deterioration because of the severe effect it has on riding surface, the reduction in structural capacity, and the difficulty in making a permanent repair. The use of deicing chemicals over the past several years has also significantly accelerated the spalling process.

This paper has been assembled from reports of many research and experimental projects and maintenance operations. It attempts to present an operational viewpoint of what can be done now to reduce deterioration of bridge decks and pavements. The many sources used are listed in the References. Reference numbers have been omitted in the text but can be furnished if requested.

RELATIONSHIP BETWEEN SPALLING AND CORROSION OF REINFORCEMENT

For over 50 years engineers have known that the products formed by the corrosion of reinforcement occupy over two times the volume of the original iron and can exert a mechanical pressure in excess of 4,000 psi. Under normal conditions, reinforcement is protected against corrosive attack when embedded in portland cement concrete. In recent years, however, both laboratory studies and statistical analysis of existing bridges have identified corrosion of reinforcement as a contributing factor in concrete spalling. Some of the more significant findings are as follows:

1. In Missouri, 87 percent of the cores taken through concrete with fracture planes exhibited corrosion of reinforcement; whereas, in areas without fracture planes, 16 percent of the cores showed evidence of corrosion. Similarly, a pending report by the Portland Cement Association states that the steel was corroded in all of the 29 cores taken through surface spalls. These data taken from existing highway structures show that most, but not all, spalls occur in locations where the steel is corroded. The data do not, however, show which occurs first.
2. A number of reinforced concrete slabs were constructed at the Portland Cement Association Laboratory in Skokie, Illinois, by using various water-cement (w-c) ratios and either ½- or 1½-in. concrete cover. These slabs were left outside and exposed to normal weather conditions except that a de-icer (flake calcium chloride) was applied after snow and ice storms. After 5 winters, all of the slabs with a ½-in. cover have rust stains on the surface. Interestingly, the slabs with high w-c ratios have a large number of rust stains but no spalls. The slabs with low w-c ratios have only a few rust stains but very pronounced spalls.
3. A test slab was constructed in Kansas to obtain an indication of the effect concrete cover has on bridge deck deterioration. The transverse reinforcement was placed at various depths from the concrete surface. A trowel point was drawn through the plastic concrete over each bar to create a vertical plane of weakness and accelerate deterioration. After 4 years, all types of spalling had occurred. During the testing period, they found that an increase in concrete cover increased the time required for both the appearance of rust stains in the concrete and appearance of spalls. After the test was completed, they removed several bars from the slab and concluded that an increase in concrete cover had reduced the corrosion of steel. From this test the following conclusion was drawn: "Repeated exposure of a reinforced concrete slab to moisture and salts appeared to create conditions of continuing corrosion of the steel and may have provided a pressure source sufficient to cause horizontal cracking and resultant spalls."
4. Engineers at the Portland Cement Association Laboratories at Skokie, Illinois, placed a prestressed wire (diameter of 0.612) in blocks 1 by 1 by 11, 2 by 2 by 11, and

3 by 3 by 11 to determine the effect of various thicknesses of cover on the corrosion of steel due to migration of chloride into the concrete. After 1 year, the wires were severely corroded in both the 1- and 2-in. blocks made from concrete with a w-c ratio of 7.8, and corrosion had started in the 1-in. blocks with a w-c ratio of 5.7.

5. Two hundred reinforced concrete test blocks ($4\frac{1}{2}$ by $2\frac{1}{2}$ by 15) were cast for testing by engineers from the California Transportation Agency. These specimens were partially immersed in a saturated solution of sodium chloride and periodically checked to monitor changes in electrical potential of the steel and appearance of rust stains or cracks in the concrete. A mathematical relationship was found between the time to an active potential and the time to cracking of the concrete due to corrosion of the reinforcement. The average time to concrete cracking due to corrosion of the reinforcement after exposure of the concrete to a salt solution averaged about 10 months.

Based on these data reviewed, it can definitely be stated that corrosion of reinforcement causes spalling.

EFFECT OF SALT ON CORROSION OF STEEL

Approximately 20 years after the original development of portland cement, a French engineer reported on the disintegration of concrete due to the action of seawater. Since that time, many research reports have been written on this subject. These reports have generally focused on the phenomenon known today as scaling. However, the effect of salt on corrosion of reinforcement in concrete has also been known for many years.

In a report published by the Bureau of Standards in 1913, E. B. Rosa wrote:

> The addition of a small amount of salt (a fraction of 1 percent) to concrete (as is frequently done to prevent freezing while setting) has a two-fold effect, viz., it greatly increases the initial conductivity of the wet concrete, thus allowing more current to flow, and it also destroys the passive condition of the iron at ordinary temperatures, thus multiplying by many hundreds of times the rate of corrosion and consequent tendency of the concrete to crack.

A search of the literature reveals that salt has the following effects leading to corrosion of reinforcement:

1. The normal passive condition of the steel is destroyed. This is generally attributed to a reduction in pH of the concrete and a subsequent loss of protective film around the reinforcement.
2. Variations in salt content, oxygen supply, or stress along the length of the reinforcement can produce an electric cell.
3. A small amount of salt greatly increases the electrical conductivity of wet concrete.
4. The corrosive products do not provide a protective coating over the reinforcement because the anode and cathode can be separated a considerable distance because of the increase in electrical conductivity.

ACCESS BY CHLORIDES TO THE REINFORCEMENT

Salt may be added to the mix, enter cracks in the deck, or penetrate the sound concrete. It is necessary to understand each of these procedures if we are to prevent corrosion of reinforcement.

Calcium Chloride Additive

Laboratory tests have shown that approximately 2 lb of salt per cu yd (6-bag mix) of concrete is sufficient to almost completely destroy the passivity of iron. The standard specifications, however, in approximately 8 states still permit calcium chloride to be added to structural concrete. This practice is potentially hazardous and should be prohibited.

Effect of Cracks

There is ample evidence of cracking that has not led to further distress. However, the importance of cracking should not be overlooked. Certainly, wide cracks permit moisture containing dissolved de-icing chemicals, oxygen, and other aggressive elements direct access to the reinforcement. In addition, cracks are subjected to mechanical pressures from particulate intrusions, formation of ice, and pounding of traffic. These forces lead to further distress of the concrete.

Salt Penetration Into Sound Concrete

As previously mentioned, numerous measurements of chloride content have been made that document the fact that chlorides can and do penetrate sound concrete to appreciable depths. Several studies have been made that show that the time required for corrosion of reinforcement and subsequent spalling of the reinforced concrete is decreased by the following factors: increase in chloride content in the environment, increase in w-c ratio, and decrease in concrete cover.

FACTORS AFFECTING THE TIME REQUIRED FOR CORROSION OF REINFORCEMENT

These study findings will be related to practical applications by examining separately each of the factors listed in the previous section.

Chloride Content in the Environment

Nationally, the increase in use of salt for snow and ice control is phenomenal. Data provided by the Salt Institute (Fig. 2) indicate that the use of salts on pavements and structures has increased approximately 4½ times since 1962. Obviously, many highways are now being subjected to a much harsher environment than that existing

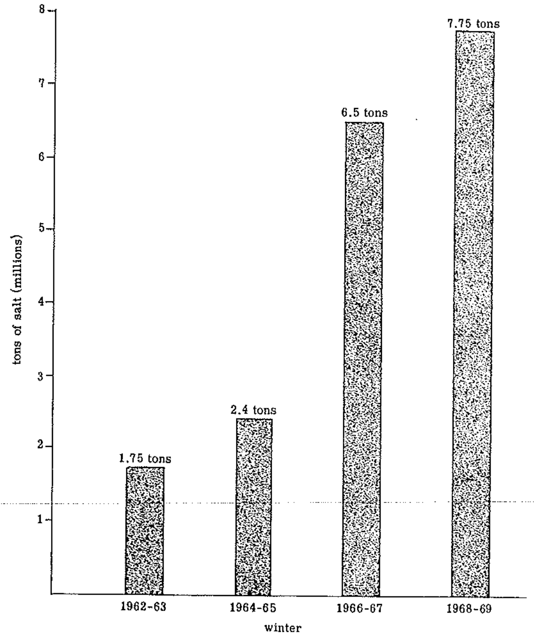


Figure 2. Use of salt for snow and ice control on highways and streets.

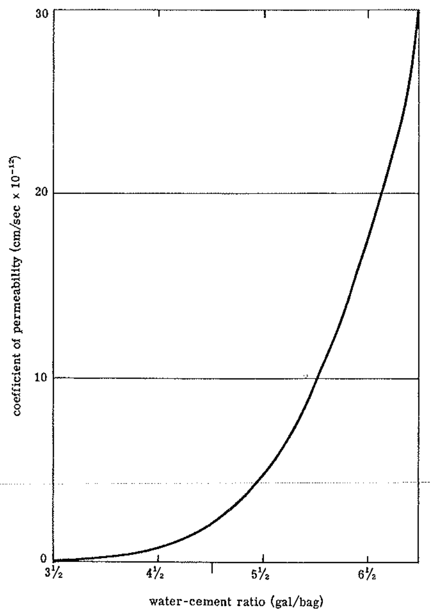


Figure 3. Relationship between the permeability of cement paste and w-c ratio.

only a few years ago. Although various noncorrosive de-icing agents have been studied, we are unaware of any such system that is both effective and economical. Because no decrease in public demand for bare pavements is anticipated, we recommend that structures and pavements containing reinforcement be designed to resist these harsh environments.

Effect of Water-Cement Ratio

Figure 3, which contains data provided by the Portland Cement Association, shows that the w-c ratio has a very pronounced effect on the porosity of cement paste. The coefficient of permeability increases rapidly with an increase in w-c ratio in excess of 5 gal per sack. Various tests have shown that the chloride content inside an uncracked concrete specimen does, in fact, increase with an increase in w-c ratio. Obviously, concrete should be as impermeable as possible. As a practical matter, a maximum w-c ratio of 5 to 5½ gal per sack appears to be the optimum balance between the requirements for workability of the mix and permeability of the paste.

Effect of Concrete Cover Over Reinforcement

A detailed study was made on the Blue Rapids Bridge in Kansas to determine the relationship between the concrete cover and the occurrence of surface spalls, hollow areas, and potholes. Figure 4 shows the general relationship of the average bar depth to the percentage of surface deterioration.

Figure 5 shows the relationship between chloride content and depth of cover for bridge decks in Kansas. Similar curves have been developed in other states. These curves and laboratory studies reveal that chloride content at the level of the reinforcement is approximately halved for each additional inch of concrete cover.

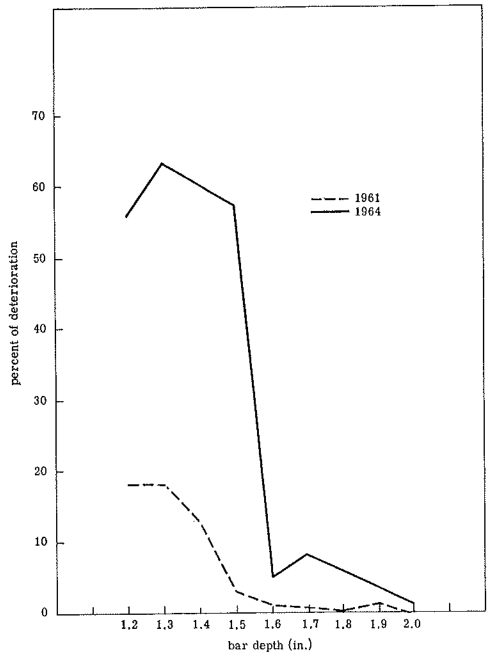


Figure 4. Average bar depth per 5-ft increment versus percentage deterioration in the same area—Blue Rapids Bridge, Kansas.

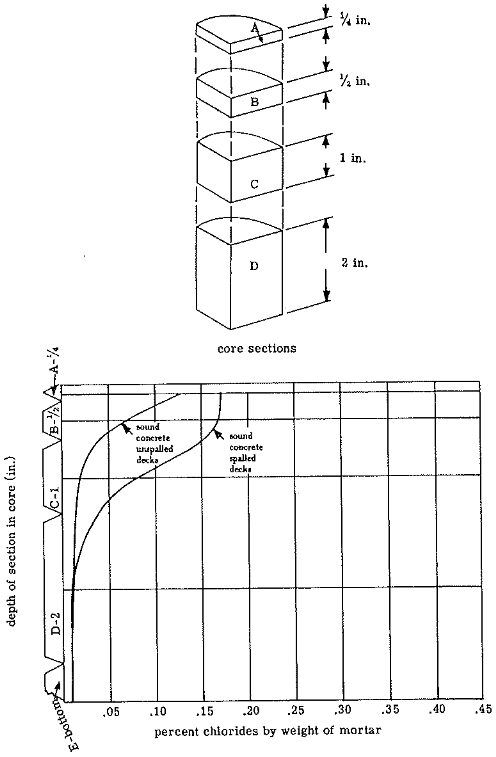


Figure 5. Relationship of chloride content and depth of cover—Kansas bridge decks.

These data indicate that the service life of the concrete deck is largely dependent on the depth of concrete cover over the reinforcement. They also indicate that a 2-in. cover should be sufficient to virtually eliminate deterioration due to corrosion of the reinforcement. There are, however, ample reasons to believe that additional cover should be specified, including the following:

1. Because the use of de-icing salts in recent years has substantially increased, past experience may be a poor indicator for use in designing for protection against future applications of these chemicals.
2. Laboratory studies by the Portland Cement Association have shown that de-icing chemicals can penetrate 2 in. of good quality concrete (5 gal per bag) in only 1 year.
3. Various agencies have recommended a 3-in. cover over the steel for reinforced concrete in a marine environment.
4. Whatever the minimum cover desired, some additional cover should be specified to provide for construction tolerances.

Certainly, a 2-in. cover is the minimum that can be expected to provide a reasonable level of protection against de-icing chemicals. An increase in cover within practical limits should result in an increase in the service life of the deck.

ACTION THAT CAN BE TAKEN NOW

The following actions can be taken now to reduce bridge deck and pavement spalling where de-icing chemicals are used:

1. Increase the depth of concrete cover over the reinforcement. We strongly recommend a minimum cover of 2 in. and would prefer 3 in.
2. Hold mixing water to a minimum. We support the recommendation of the Portland Cement Association that the w-c ratio should not exceed 5 gal per bag.
3. Use high cement contents. Cement content should be a minimum of 7.0 bags per cu yd for $^3/_4$-in. maximum size aggregate as recommended by the Portland Cement Association.
4. Keep cracking to a minimum. Suggestions to accomplish this are as follows: (a) keep heavy construction equipment off the new decks and pavements for as long as reasonably practicable, (b) do not add water or grout to the surface of the plastic concrete and fill low areas with additional concrete and rescreed, (c) schedule deck pours to avoid adverse weather conditions, including high temperature, low humidity, and high winds, which have more effect on cracking than do construction practices, (d) keep mix temperature as low as practicable, (e) begin curing when surface moisture disappears, and (f) have size and spacing of transverse reinforcing as large as design will permit in order to reduce horizontal cracking.

FUTURE ACTION

Will the reinforcement in future bridge decks be protected by additives to concrete, coatings on the reinforcement, cathodic protection, or waterproofing treatments? Waterproofing treatments have gained in popularity and appear to be the best approach for future construction because an effective system would protect the deck against both spalling and scaling.

Information is needed on the cost-effectiveness of these waterproofing treatments. We also need to identify the corrective treatment for spalls that provides the best service life. In addition, bridge piers and reinforced concrete pavements should be reviewed to determine if the chlorides are acting on the reinforcement. We believe work in these areas will provide answers that will reduce future maintenance costs.

Solutions to these problems should be easier to attain as a result of efforts by the California Division of Highways. It has developed a nondestructive device that can measure the electrical potential between the reinforcement and surrounding concrete. As corrosion begins, this electrical potential increases and continues to increase as the corrosion process advances. With this device engineers will be able to determine if the reinforcement is corroding in either prestressed or conventional concrete structures. In addition to its other uses, this device will reduce the time required to evaluate the effectiveness of corrective and protective treatments. We believe this to be a major breakthrough and that further development and field evaluation in other states are warranted. Therefore, a project has been set up within the Bureau of Public Roads to demonstrate this device on bridge decks and pavements at no cost to any agency desiring a demonstration.

The use and performance of protective treatments is currently being evaluated in the field. A status report is tentatively scheduled for publication by August. Corrective treatments are also being studied.

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Formal Discussion

J. D. Shackelford

This paper does an excellent job of bringing together the many different and varied sources of research on the subject of the effects of salts on bridge and pavement deterioration. However, in the monumental task the authors had of searching through the available information, they overlooked several references relating to the use of calcium chloride as an additive to structural concrete and the effect of such an additive on the corrosion of reinforcing steel. These references have a very significant bearing on the conclusions that were presented in this paper.

The authors refer to a 1913 report by E. B. Rosa relative to the effect on the passive condition of iron at ordinary temperatures when adding calcium chloride to the concrete. Following this train of thought a little further, I find a later report that states (38):

> It has been established that calcium chloride incorporated in concrete does not contribute to corrosion of steel in concrete. It has been shown by Wells (50) that the calcium chloride combines with the chemical constitutents of the cement very early and no longer exists in the concrete in the form of a salt. Actually, a very dilute salt solution exists only during the plastic stage of the concrete.

In addition, the following are statements from only a sample of reports relative to this subject:

1. In 1923, Cottringer and Kendall (26) found after one year no corrosion of ¾-in. bars in 6- by 6- by 24-in. long concrete specimens mixed with 0 to 10 percent calcium chloride. Also another report in 1923 (38) stated that "steel in 1:2:4 concrete and 1:3 mortar specimens (was) examined by the U.S. Bureau of Standards (23) after outdoor storage for 5 or 6 years. Tests (were) also made using metal lath in slabs. Corrosion of metal due to calcium chloride was not serious nor of progressive nature when metal was completely embedded. Pockets near reinforcing should be avoided."
2. Mattimore (24) reported as follows: "The plain concrete slabs were cured by being kept wet for eight days and were not opened to traffic for twenty-one days, while the calcium chloride concrete was kept wet for only two days, from that time during the remainder of the seven-day period it was not covered, while at seven days it was open to a normal traffic on one of our main routes. Attention is also called to the fact that the concrete with a 2 percent solution of calcium chloride shows higher compressive strength than does the concrete to which a 4 percent solution has been added. Recent data on calcium chloride check this result. These concrete slabs were reinforced with cold-drawn wire mesh, and an examination of the steel showed no detrimental action of the calcium chloride.
3. Pearson (25) reported the following: "The majority of people would pass upon them (steel rods) as being entirely satisfactory. Corrosion is absent over the greater portion of the surfaces of the rods, what rust occurred being localized apparently where

voids occurred on the surface of the steel. Comparison of the one year and five year specimens indicates that corrosion is not progressive."

4. A report by Swallow (31) states: "It may be remarked that the only places where rusting of steel in concrete has been observed experimentally are in positions where rusting would have occurred in any case, and that lack of proper contact between concrete and reinforcement should be regarded as a serious defect, and it is only under such conditions that rust has been observed. There is no evidence to show that rusting is worse in calcium chloride concrete or that the rusting is progressive. By increasing the fluidity of a concrete mix, the calcium chloride addition should assist placing and help to assure good contact with the reinforcement. To this extent it may be said to assist in preventing corrosion."

5. Libberton (27) in a written discussion stated: "In construction work generally there have been many cases where the rusting of reinforcing has menaced either the appearance or the strength of a building and with that in mind we have endeavored for some years to determine any cases of rusting where calcium chloride was used in the concrete. While calcium chloride or compounds depending largely upon it for their efficiency have been used in very large quantities during the past ten or fifteen years, we have yet to find a case of rusting in actual construction where calcium chloride was incorporated in the concrete."

It appears from these sources (and others listed in the References) that the conclusion reached by the authors is not valid.

The conclusion as stated in the paper suggests that calcium chloride should be prohibited from use as an additive to structural concrete. I believe that this conclusion is in error when viewed in terms of the overwhelming amount of evidence that shows that the corrosion of steel in concrete with calcium chloride admixture is not different from that in concrete containing no admixture, and has been proven many times to be nonprogressive.

Certainly calcium chloride is a material that has to be used with engineering judgment. As a supplier of calcium chloride, we do not recommend its use in all applications, such as when the temperature is too high (40), when prestressed concrete (39) is being cast, or when aluminum (42) or other di-metal systems are present. However, when justifiable conditions prevail, there should be no hesitancy on the part of an engineer or architect to specify the use of calcium chloride as an additive for structural concrete.

These comments are directed only toward the use of calcium chloride as an additive to concrete. The problem associated with de-icing salts (much more sodium chloride used than calcium chloride) penetrating concrete and causing or accelerating corrosion is another subject. No doubt this is a major problem facing the industry today, and the authors have done a good job summarizing the various factors contributing to this situation.

I was pleased to see the authors continue with suggested remedies and methods in which a more durable structure could be obtained, specifically relative to bridge decks. It was somewhat disappointing that no reference was made to the use of latex-modified portland cement compositions as a possible solution to providing more durable, resistant wearing surfaces for bridge decks. This modified system allows the placement of relatively thin sections (as little as $^3/_4$ in.) of modified portland cement compositions to either existing or new structures. This material has the capability of bonding to a clean, sound substrate with a strength equal to or greater than the strength of the substrate itself. The material has demonstrated by experience over a 10- to 13-year period in field applications as well as laboratory studies to be greatly more resistant to freeze-thaw damage in the presence of salt brines.

One thing that is stressed in the comments and references mentioned (both in the paper and this discussion) is controlling the w-c ratio of the composition. One of the highlights of the latex-modified portland cement composition is the fact that the water used in this particular system is less than 4 gal per sack of cement (w-c ratio of 0.34 to 0.37). Also, this system does not sacrifice workability at that low w-c ratio as this material still has a slump of 5 to 7 in.

By the nature of this system (formation of plastic films as well as higher density because of lower w-c ratio), this material is less permeable than unmodified portland cement compositions. Tests are currently being made to measure the migration of sodium and calcium chloride de-icing salts into this system from both laboratory specimens and field cores.

Other factors that contribute to the success of this approach are that the modulus of elasticity is approximately half that of unmodified compositions at the same time the flexural strength is considerably higher. On a "living" bridge deck, these properties are very important. Because the bulk of the modified system consists of portland cement, sand, aggregate, and water, the composition has essentially the same coefficient of thermal expansion as unmodified compositions. Also, the modified system has the same color appearance, and the surface can be texturized to any degree of roughness desired. Several reports on the use and performance of this system are available (43, 44, 45, 46, 47, 48, 49).

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Hall and LaHue

The 2 points raised by Mr. Shackelford pertain to the discussion of calcium chloride additives to concrete and the omission of a reference to Dow Chemical's latex-modified portland cement bridge deck overlays. The lack of reference to the latex overlay was not intentional. Reports on this method of repairing bridge decks have been distributed nationally by the Bureau of Public Roads in the construction and maintenance bulletins. We believe this type of overlay shows promise, but, because field evaluations are still under way in many states, an official position by the Bureau of Public Roads at this time would appear premature.

Concerning the discussion of chloride additives to concrete, we stated in our paper: "Laboratory tests have shown that approximately 2 lb of salt per cu yd (6-bag mix) of concrete is sufficient to almost completely destroy the passivity of iron. The standard specifications, however, in approximately 8 states still permit calcium chloride to be added to structural concrete. This practice is potentially hazardous and should be prohibited."

We refer here specifically to chloride additives used in bridge deck concrete. We have studied the quotes in Mr. Shackelford's discussion. We have also reexamined our reference sources on this subject. Considering all the data available, we retain our position on this matter. Future editions of this paper will include an additional recommendation as follows: Prohibit the addition of calcium chloride as an accelerator in concrete that is to be placed in bridge decks.

We can agree with Mr. Shackelford on one point in his discussion, and that is "... calcium chloride is a material that has to be used with engineering judgment."

It is discussions such as these that assist all highway engineers in achieving the best possible product. We appreciate the time taken by Mr. Shackelford to respond to our paper.

Informal Discussion

Lorne W. Gold

Investigations have been made on the possible effect of salt, and considerable scaling or spalling is found with specimens that do not contain steel. Do you care to comment on that?

Cunningham

I am not familiar with any area of the country where this is occurring. Our review was mainly confined to bridge decks containing steel.

Samuel Nitzberg

Have you had any experience with concrete construction in which vibrations and extreme cold together cause the concrete to disintegrate?

Cunningham

No, But I can see that this type of disintegration could occur under the given circumstances.

Nitzberg

Have you noticed that in the cold weather areas there are always potholes and large disintegrated areas that occur within a year or two on all bridges always at the apex?

Cunningham

Our office has not received any reports of this type of concrete disintegration.

Nitzberg

In our study we find that the longer the bridge is, the greater the vibration, and that the colder the weather is, the worse the disintegration of the concrete. It just breaks up and crumbles into potholes.

Cunningham

In what state?

Nitzberg

I have noticed it in New Jersey and New York. In fact I found this condition throughout the country in a study I made of it. Yet, in the South, in Florida, South Carolina, and Georgia, I have not seen this condition.

Cunningham

We found that disintegration of concrete on bridge decks was confined mainly to the northern states where there is freezing and thawing and where chemicals are used. In the southern states, we have found very little concrete bridge deck disintegration.

Jerrold L. Colten

Do you have any correlations on the effective life of prestressed portable spans now being used?

Cunningham

No.

Don L. Spellman

I would like to say amen to all of Mr. Cunningham's recommendations. I am a pessimist, however, because I feel that even if we follow all these recommendations, which are really just good concreting practices, we are still not going to stop bridge deck deterioration. We may be able to slow it down, and, if we can stop it for 20 years, we still are better off. But sooner or later the salt is going to penetrate, and when it reaches the steel we will have trouble.

John Pendleton

Do you have any comment on what I guess you would call the malpractice of using rusted steel reinforcement fresh concrete? Do you get any effect from this?

Spellman

I think we would because of differential conditions from one part of the steel to another, and this tends to create electrolytic cells responsible for corrosion. At least our studies of potential measurements of steel and concrete show we already have a cell condition set up.

Kaare Flaate

We have problems with concrete bridge decks in the heavily populated areas where salt is used to melt ice and snow. We get spalling and, it seems to us that this spalling occurs primarily because of the reduced quality of the concrete and that the spalling is increased by the heavy traffic of studded tires. I am not quite sure that the reinforcement is so important. In some instances, the concrete deteriorates all the way down to the reinforcement and even further. It just happens that the reinforcement is there and tends to add something to the deterioration of the whole bridge deck. But the main reason for the deterioration seems to be the salt, frost, and dynamic effects, and I believe it can go much deeper than to the reinforcing steel. Even in very cold weather with light traffic and no salt, we have no problems. We thought we were doing something good by putting an asphalt cover on top, but this is probably worse than anything else if it is not really waterproof. So what we are trying to do now is get a waterproof deck that can move with respect to the underlying concrete.

Lawerence H. Chenault

Some years ago we did a snow-melting heating installation in a carwash where spalling was a real problem. I realize this is not a bridge, but it is an example of a heating system installation over a very badly spalled concrete deck. We placed 3 in. of concrete and used an acid etch and then a detergent solution to clean the concrete prior to the bonding of the new overlay. This has been in use for 4 years, and there has been no detachment or failure of this bonded overlay.

John Sayward

I do not know whether this is an explanation of the spalling, but it may have some similarity to what is known as salt weathering, which again is something related to frost action. In salt climates salt gets into porous rocks and then evaporates. The moisture gets out, but the salt starts to crystallize and keeps growing inside, unable to migrate through the small passages. This is much the same mechanism that exists with frost action. It creates a pressure just as the corrosion of the iron causes pressure, as stated by Mr. Cunningham. Why would this not be possible, granted there is a permeability of some degree to the concrete.

Gold

I think it is quite true that there are a number of things we still do not understand about this particular problem.

James A. Murchie

I wonder if anyone would care to comment on continuously reinforced concrete pavements inasmuch as their defects seem to compare with those in bridge decks. We are getting a problem now, and it sounds like this one being discussed. Although the mechanism is slightly different, we are getting the same ultimate effect; that is, we are actually losing steel.

Glenn G. Balmer

One of the fundamental principles in making good concrete, as has already been stated by Mr. Cunningham, is to keep the water content low. To make good concrete requires that as small an amount of water as practical be used. Of course, an adequate amount of cement is essential. Scaling is a surface phenomenon and may occur on concrete without steel. Too much water in concrete causes bleeding. The surface of the concrete is weakened from overworking or from too much water coming to the top. Strength-producing components of the concrete settle, leaving the surface weak. Another important factor in making good concrete is to use an air-entraining agent. Concrete should have on the order of 5 to 7 percent air. This is a means of mechanically resisting freeze-thaw cycles. The microscopic air bubbles in the concrete permit expansion and contraction to take place without causing failure of the concrete, or at least they decrease the failure. Spalling is a problem somewhat separate from scaling. Spalling is often caused by variation in stress. The stress may be from differential expansion or contraction or from external loads.

William F. Limpert

Has any work been done on coating reinforcing rods? If so, have there been cost effectiveness comparisons made between coating the rods to prevent the corrosion and laying another 2 in. of concrete on top of it?

Spellman

I believe galvanized reinforcing bars were put in some bridge decks in Michigan, but I have not seen any results.

Pavement Heating

Frank Winters

An experimental, heated pavement has been constructed in Trenton, New Jersey, by the New Jersey Department of Transportation in order to develop improved methods for snow and ice control. The experimental pavement serves the dual purposes of (a) providing design data for snow-melting systems of embedded pipe, and (b) utilizing the earth both as a source of heat and as a means of storing solar energy. Wrought iron pipes of various diameters are embedded in portland cement concrete and bituminous concrete at depths of 2 and 4 in. and at various spacings. During snow and ice conditions an ethylene glycol solution is circulated through these pipes, and a record is kept of the flow rate and temperature drop of the heating fluid. The effectiveness of any particular combination of pipe diameter and spacing and depth of embedment may be evaluated by observing the rate at which the snow melts and by calculating the amount of heat supplied to the pavement by the embedded pipes. Heat is extracted from the earth by means of a buried heat exchanger consisting of 6,000 ft of $1\frac{1}{4}$-in. wrought iron pipe. The earth beneath the pavement was excavated to a depth of 13 ft, and 5 layers of pipe were laid with a horizontal and vertical spacing of 2 ft as the pit was backfilled. Heat is transferred to the surface by circulating the ethylene glycol solution through the buried pipe heat exchanger and then to the pipes embedded in the pavement.

The presence of snow or ice on highways, especially at interchanges, ramps, and bridge decks, often results in hazardous driving conditions and reduced traffic volumes. Conventional snow and ice control techniques may prove inadequate at these locations because of limited snow storage areas; the time lag between ice and snow formation and plowing, salting, and sanding operations; and alternate freezing and thawing of plowed or unplowed snow across superelevated ramps.

The ideal solution for the control of snow and ice at these problem locations is the use of heated pavement, capable of melting any snow or ice forming on the roadway. The major obstacle presently limiting the use of heated roads in New Jersey and elsewhere is the high operating cost of such an installation. The development of methods that would result in lower operating costs may justify the more extensive use of heated roadways.

The 2 principal types of heating systems currently in use are (a) a grid of electric resistance wires embedded in the pavement, and (b) a network of pipes embedded in the pavement, through which a hot fluid is circulated. In the latter system, the heat is usually supplied by a conventional gas- or oil-fired boiler or from commercially available steam. A unique exception is the use of natural hot springs in Klamath Falls, Oregon.

Prior work by the New Jersey Department of Transportation resulted in the construction of 2 electrically heated pavements, utilizing copper-sheathed, mineral-insulated resistance wires. The first installation was in 1961 on the approaches of Routes 1 and 9 to the Passaic River Bridge in Newark. This installation was later abandoned because of dislodgement of the cables in the bituminous concrete overlay. An improved installation was constructed in 1964 on 2 ramps and a bridge deck at the interchange of US-46 and US-17 in Teterboro. This system has operated satisfactorily for the past 5 years in melting any snow or ice on the pavement surface. Both installations were designed to dissipate 30 to 40 W/sq ft, which resulted in an annual operating cost of approximately 45 cents/sq ft of pavement surface.

This project was designed to experimentally evaluate the sources of ground and solar heat. Previous studies have shown that at a depth of 10 ft the soil temperature averages 55 F with a seasonal variation ±5 F and with the minimum occurring in March or April. At deeper depths the temperature gradually increases and exhibits less seasonal variation. To tap this heat source, a heat exchanger consisting of a network of pipes was buried in the earth through which an antifreeze solution was circulated. The antifreeze solution was then circulated through a grid of pipes embedded in the pavement, thus transferring heat from the earth to the pavement surface. During the summer months radiant energy from the sun often heats pavement surfaces to temperatures in excess of

PORTLAND CEMENT CONCRETE

PANEL No. 1 3/4" WROUGHT IRON PIPE	PANEL No. 3 1" PLASTIC PIPE	PANEL No. 5 1-1/4" WROUGHT IRON PIPE	PANEL No. 7 ELECTRIC RESISTANCE WIRES
PANEL No. 2 3/4" WROUGHT IRON PIPE	PANEL No. 4 1" WROUGHT IRON PIPE	PANEL No. 6 1-1/4" WROUGHT IRON PIPE	PANEL No. 8 ELECTRIC RESISTANCE WIRES

BITUMINOUS CONCRETE

Figure 1. Plan view of experimental area.

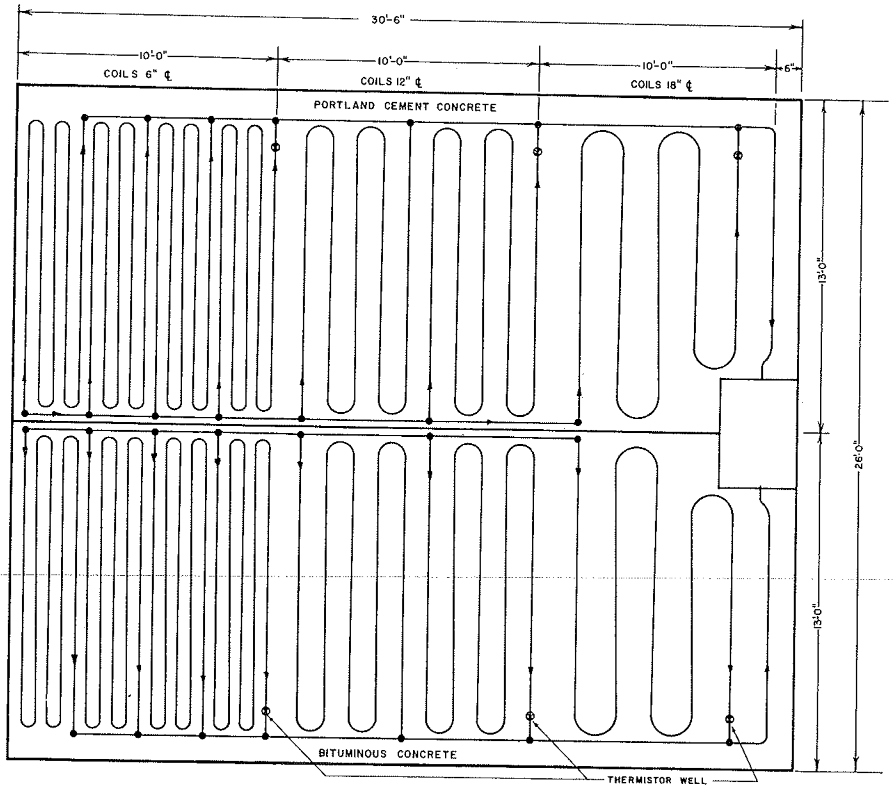


Figure 2. Typical heating panel.

100 F. This heat may be transferred from the pavement to the earth for storage by utilizing this same system of pipes.

Because construction of the experimental area was not completed until December 1969, this paper is limited to the evaluation of the use of ground heat. This report contains information on the design and construction of the experimental heated pavement and results obtained during the 5 major snowstorms from December 25, 1969, to February 26, 1970.

DESIGN OF PAVEMENT

The experimental heated pavement is located in the Fernwood Parking Lot adjacent to the Transportation Department Building in Trenton. The test area consists of 2 parallel lanes of pavement, each 13 ft wide and 123 ft long. One lane consists of four 9-in. thick slabs of portland cement concrete (pcc) while the other lane is constructed of 7 in. of bituminous concrete (bc) on a 6-in. macadam base. Each lane is subdivided into 8 separate test panels. Each panel is independent from the others so that a single malfunction will not affect operation of the entire system.

Pipes with nominal diameters of ¾, 1, and 1¼ in. are embedded at depths of 2 and 4 in. in the pavement of panels 1 and 2, 3 and 4, and 5 and 6 respectively (Fig. 1). In each of these panels the pipes are spaced on 6-, 12-, and 18-in. centers as shown in Figure 2. All pipe is standard weight wrought iron except in panel 3 where a polyvinyl chloride plastic pipe is used.

To serve as a reference, panels 7 and 8 contain vinyl insulated electric resistance wires embedded at a depth of 2 in. Both panels are evenly divided into 3 sections, designed to dissipate 20, 40, and 60 W/sq ft (Fig. 3). In addition, there is a 2-in. layer

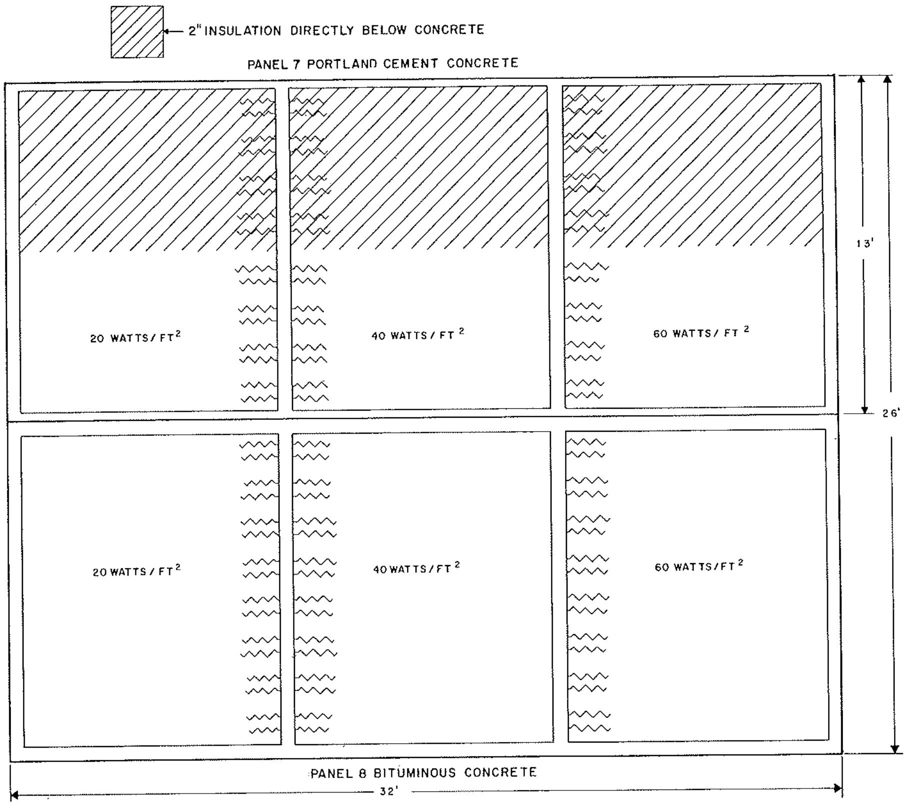


Figure 3. Typical electrically heated panel.

of glass foam insulation directly below half of the electrically heated portland cement concrete slab (panel 7). This insulation was included to test its effectiveness in reducing downward heat losses.

DESIGN OF HEAT EXCHANGERS

There are 3 heat exchangers (Fig. 4) each consisting of approximately 2,000 linear ft of $1\frac{1}{4}$-in. wrought iron pipe. Heat exchanger 1 is buried beneath panels 1 and 2, heat exchanger 2 is below panels 3 and 4, and heat exchanger 3 is below panels 5 and 6. Each heat exchanger is independent of the others and is connected to a separate pump that circulates an antifreeze solution of 50 percent water and 50 percent ethylene glycol to the 2 panels directly above it.

Because it is probable that much of the solar heat stored in the earth during the summer months may dissipate to the atmosphere or the surrounding earth, an 8-in. horizontal layer of insulation was provided above heat exchangers 1 and 2. In addition, a 6-in. layer of insulation completely encloses heat exchanger 2 (Fig. 5). This insulation is an expanded polystyrene foam having a density of 1.5 lb/cu ft for the 8-in. layer and 1.0 lb/cu ft for the 6-in. layer.

Heat exchanger 3 has not been insulated in order to serve as a control.

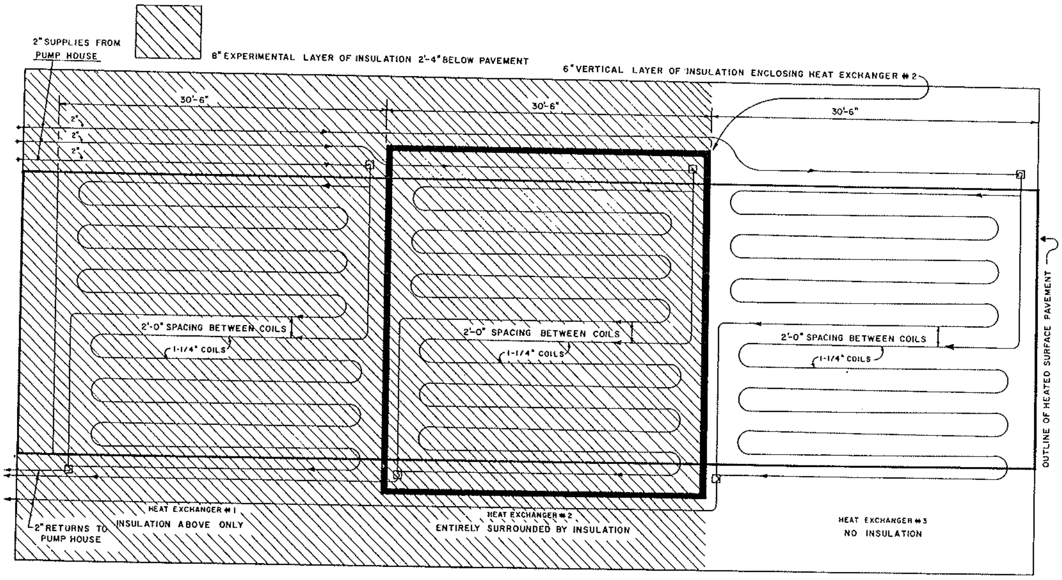


Figure 4. Plan view of heat exchangers.

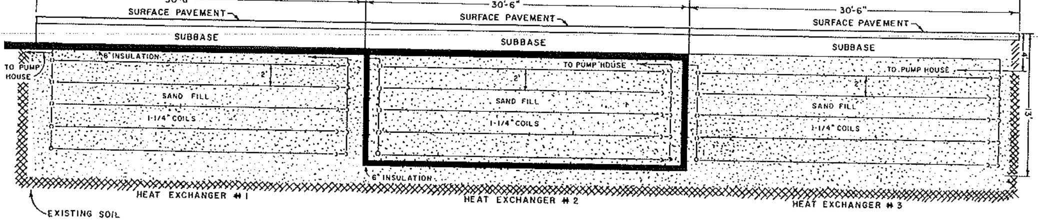


Figure 5. Section view of heat exchangers.

INSTRUMENTATION

Temperature of the earth, pavement, and water-glycol solution are monitored by 114 thermistors. Flow rate of the water-glycol solution is measured with 3 glass-tube, variable area flow meters.

TABLE 1

GRADATION REQUIREMENTS

Sand or Aggregate	Type	Square Sieve Size	Percent Passing
Sand backfill for heat exchangers	4E	½ in.	100
		No. 4	95 to 100
		No. 30	20 to 55
		No. 50	5 to 25
		No. 200	0 to 5
Aggregate for portland cement concrete	SPR 57	1½ in.	100
		1 in.	95 to 100
		½ in.	25 to 60
		No. 4	0 to 10
		No. 8	0 to 5
Aggregate for bituminous concrete	Mix 5	½ in.	100
		¾ in.	90 to 100
		No. 4	60 to 80
		No. 8	41 to 51
		No. 50	14 to 22
		No. 200	4.3 to 8.8

CONSTRUCTION OF HEAT EXCHANGERS

Construction began on April 7, 1969. A 100- by 40-ft area was first excavated by bulldozer to a depth of 14 ft. All excavated material was trucked away because it was not considered suitable for backfill. A 6-in. layer of sand backfill was then spread over the entire area and compacted with a small hand-operated compactor (Table 1). In the area of heat exchanger 2, a 6-in. horizontal layer of polystyrene insulation was placed on the sand base (Fig. 6). This layer was constructed from 4-ft by 8-ft by 3-in. sheets of insulation with all joints overlapped. Another 6-in. layer of sand backfill was then placed over the entire area and compacted. Some difficulty was encountered in compacting the sand above the insulation because of its resiliency; however, as successive layers of backfill were placed, it was possible to achieve the specified compaction of at least 95 percent of maximum density. Prefabricated 1¼-in. wrought iron coils were then placed on the compacted sand (Fig. 7). All pipe joints were gas welded and tested for leaks by pressurizing the coils at 150 psi for 8 hours.

The same sequence of operations of placing and compacting backfill in 6-in. layers and the placement and testing of 1¼-in. coils with a 2-ft separation between layers continued until all 5 layers of the heat exchangers were completed.

The 6-in. thick vertical walls of insulation enclosing heat exchanger 2 were constructed of 4-ft by 8-ft by 3-in. sheets with all joints overlapped. Upon completion of backfill operations, an 8-in. horizontal layer of polystyrene insulation, constructed of 4-ft by 12-ft by 4-in. sheets, with all joints overlapped, was placed above heat exchangers 1 and 2.

Subsequent to placing the 8-in. layer of insulation, construction of the subbase and base courses for the surface pavement proceeded in a conventional manner. The only

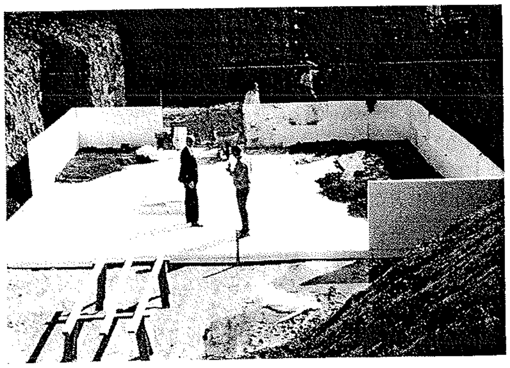


Figure 6. Polystyrene insulation enclosing heat exchanger 2.

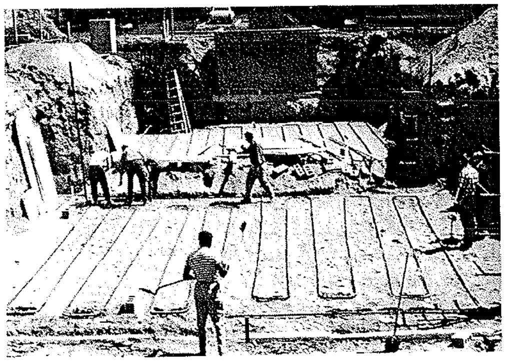


Figure 7. Wrought iron coils on sand backfill in heat exchanger 2.

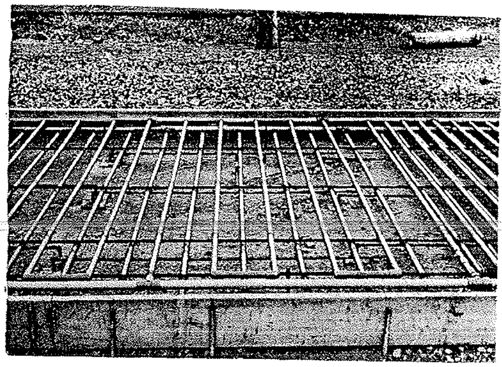


Figure 8. Plastic pipes in panel 3.

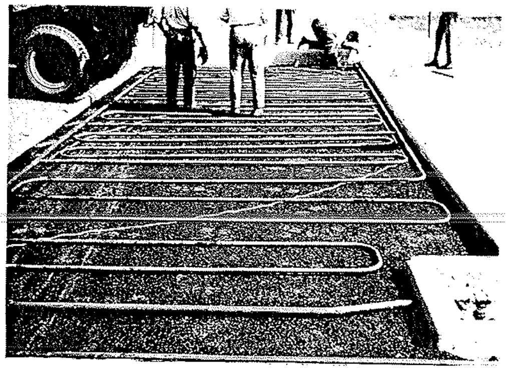


Figure 9. Wrought iron pipes in panel 2.

precaution taken was to maintain at least 6 in. of subbase material above the insulation during operation of heavy construction equipment.

CONSTRUCTION OF PORTLAND CEMENT CONCRETE

Upon completion of the subbase and base courses, forms for the pcc slabs were installed and the prefabricated wrought iron coils were placed within the forms at the specified heights by the use of "chairs," fabricated from ½-in. reinforcing rods. All pipe joints were gas welded and pressure tested at 150 psi for 8 hours. The coils for panel 3 were fabricated at the site from standard weight polyvinyl chloride plastic pipe (Fig. 8). All joints were solvent welded and pressure tested at 150 psi for 8 hours.

Portland cement concrete for this project was a standard mix as used in a typical New Jersey state highway. Placement, finishing, and curing of the concrete was accomplished according to standard state specifications for highway construction.

CONSTRUCTION OF BITUMINOUS CONCRETE

The bituminous concrete was placed in 4 lifts on a 6-in. macadam base course. After the first lift was placed and compacted, the prefabricated wrought iron coils to be embedded at a depth of 4 in. were placed on the hot surface, and placing and compaction of the second lift began (Fig. 9). This operation was again repeated for the next layer of coils to be embedded at a depth of 2 in. The bituminous concrete was placed mostly by hand, although a spreader was used for the bottom and top course. A 5-ton, 2-wheel roller was used to compact all 4 lifts. The only problem encountered was warping of the iron pipe due to heat from the hot mix. This may have resulted in the formation of voids either above or below some of the coils.

THERMISTORS

Thermistors with the heat exchangers were placed during the backfill operations. Thermistors in the earth adjacent to the heat exchangers were fastened to a wooden rod, at specified intervals, which was then inserted into a hole drilled to the proper depth. Positioning of the thermistors in both the pcc and the bc was by means of ½-in. wooden dowels driven into the base courses. The thermistors were inserted into holes drilled through the dowel and then secured with plastic tape. Figure 10 shows a section view of the heat exchangers and the depths and relative positions of the thermistors and the 1¼-in. pipes. The columns of thermistors shown are located in the center of each heat exchanger. The column of thermistors in the control section is located 40 ft from heat exchanger 3.

Construction and testing of the system was completed on December 19, 1969, at which time it became operational.

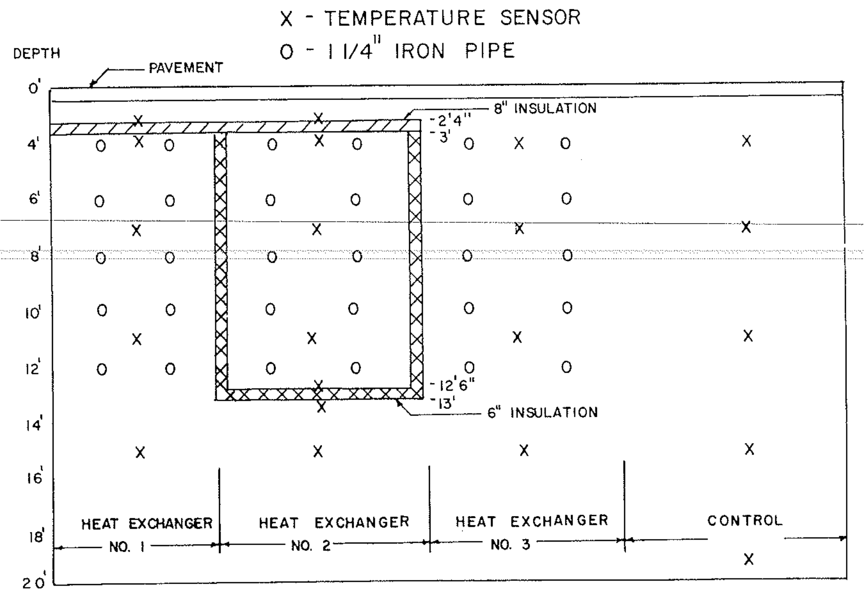


Figure 10. Section view of experimental area and thermistor location.

RESULTS

Results presented here are for 5 snowstorms, each of which resulted in an accumulation of 1 in. or more.

December 25, 1969

Snowfall began at approximately 4:00 p.m. and continued until early morning of December 26, resulting in a total snow accumulation of 3 to 4 in. All panels were activated at 9:55 p.m. December 25, at which time there was an accumulation of 2½ in. of snow. Within an hour the snow above the wrought iron pipes spaced on 6-in. centers (panels 1 and 5) began to melt and turn to slush. Complete melting in these areas was accomplished by 4:15 p.m. December 26, 1969. At this time there was localized melting directly above the pipes spaced on 12- and 18-in. centers in the same panels. Although there was some melting on panel 3 (plastic pipe in pcc) and panels 2, 4, and 6 (wrought iron pipes in bc), the surface was still covered with 1 to 2 in. of snow.

Throughout the operation, melting of snow on panels 1 and 5 above the 6-in. spaced pipes was at least equivalent to the 20 W/sq ft area of panel 7 (electrically heated pcc).

The system was kept in operation until 10:00 a.m. on December 29.

January 6, 1970

All panels were put in operation at 3:30 p.m. in anticipation of snow. Snowfall began at 8:00 p.m. and continued throughout the night producing an accumulation of 3 in. At 11:00 p.m. all panels except the 40- and 60-W areas of panels 7 and 8 were snow-covered. At 10:00 a.m. the next day, the area above the pipes spaced on 6-in. centers in panels 1 and 5 was clear of snow (Figs. 11 and 12). There was also localized clearing of snow directly above the pipes spaced on 12- and 18-in. centers. Panels 2, 4, 5, and 6 were covered with 1 to 2 in. of snow.

It was again observed that the rate of snow melting above the 6-in. pipes in panels 1 and 5 was at least equivalent to the electrically heated area dissipating 20 W/sq ft.

The system was turned off at 9:30 p.m., January 7.

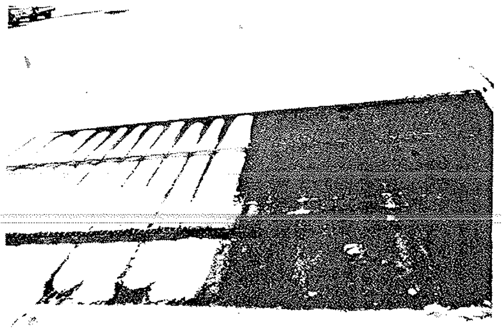


Figure 11. Panel 1 at 10:00 a.m. on January 7, 1970—pipes on 6-in. centers.

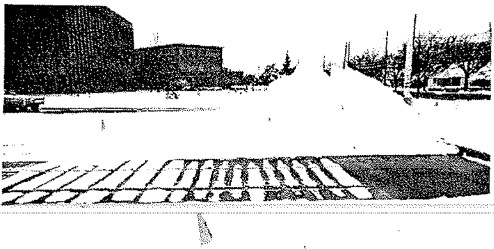


Figure 12. Panel 1 at 1:15 p.m. on January 7, 1970—pipes on 6-, 12-, and 18-in. centers.

January 12, 1970

One inch of snow fell during the night, and all panels were put in operation at 10:15 a.m., January 13. Clearing of the area above the pipes spaced on 6-in. centers in panels 1 and 5 was complete by 2:15 p.m. At this time panels 2, 3, 4, and 6 were still snow-covered.

The system was turned off at 11:45 p.m., January 13.

January 20, 1970

Snow flurries began at 5:00 p.m. and continued until 12:00 p.m. producing an accumulation of 2½ in. Panels 1, 2, 3, 4, 7, and 8 were activated at 11:45 p.m., January 20, at which time the air temperature was 28 F. During the night melting had taken place above the 6-in. pipes in panel 1. Above the electrically heated panels 7 and 8, however, all the areas refroze except the 60-W/sq ft areas of panels 7 and 8 when the air temperature dropped below 15 F.

The system was kept in operation until 11:20 p.m. on January 21 at which time the area above the pipes spaced on 6-in. centers of panels 1 and 2 was clear and dry.

February 14, 1970

Approximately 1 in. of snow fell during the day. Panels 1, 2, 3, 4, 7, and 8 were put in operation at 12:45 p.m., February 15. At 1:30 a.m., February 16, the area above the 6-in. pipes in panel 1 was 75 percent clear of snow. Panels 2, 3, and 4 were still snow-covered at this time. At 10:10 p.m., February 16, all areas of panels 1 and 2 were clear and dry.

The system was turned off at 10:00 a.m., February 17, at which time panels 3 and 4 were completely clear of snow.

FINDINGS

During all of these snowstorms, the rate of snow melting on the uninsulated section of the electrically heated pcc panel 7 was greater than on the insulated area. The 20 W/sq ft of the uninsulated area appeared equivalent to the 40 W/sq ft area of the insulated area.

Table 2 gives the amount of heat dissipated per square foot of pavement surface, and the corresponding surface temperature for the 5 major snowstorms. The heat dissipated was calculated from measurements of the input and output temperatures of the heating fluid for each spacing of coils in the various panels and from the flow rate of the heating fluid. The data were collected under approximately the same conditions. The hours of operation of the system were in the range of 7 to 12 hours, and the pavement surface was at least wet and in most instances covered with snow.

TABLE 2

HEAT DISSIPATED AND SURFACE TEMPERATURE OF HEATED PAVEMENT, ALL SNOWSTORMS

Date, Time, and Hours in Operation	Air Temperature (deg F)	Pipe Diameter (in.)	Heat Dissipated by Pipe Spacing (Btu/sq ft)						Surface Temperature by Pipe Spacing (deg F)					
			Portland Cement Concrete			Bituminous Concrete			Portland Cement Concrete			Bituminous Concrete		
			6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.
12-26-69 10:05 a. m. 12	34.4	¾	105	60	26	50	—	18	34.6	33.9	32.3	36.5	33.1	32.6
		1	72	42	13	69	46	35	33.2	32.3	32.1	36.6	33.3	32.7
		1¼	115	51	19	—	19	5.8	33.7	32.5	—	36.0	33.5	33.6
1-6-70 11:15 p. m. 7	29.0	¾	75	42	20	37	—	12	33.9	32.6	32.2	35.6	32.9	32.3
		1	51	26	11	43	27	9	32.8	32.3	32.1	35.1	—	32.6
		1¼	80	38	15	49	17	6	33.2	32.4	—	35.5	33.3	33.3
1-12-70 8:00 p. m. 12	27.5	¾	82	48	22	39	—	12	32.8	32.3	31.0	28.1	32.1	31.0
		1	50	31	10	45	35	10	32.6	27.5	26.6	34.7	28.0	28.2
		1¼	93	46	18	65	23	8	32.2	28.5	—	33.9	29.3	35.1
1-21-70 9:05 a. m. 9	16.0	¾	98	53	24	51	—	15	31.2	32.2	30.6	35.0	32.1	30.6
		1	47	30	10	41	29	8	32.6	28.2	28.7	34.7	32.0	30.5
		1¼	not operational						28.7	28.1	—	29.0	28.4	28.4
2-16-70 1:30 a. m. 12	33.4	¾	81	54	25	35	—	14	34.6	32.9	32.7	35.5	33.8	33.8
		1	52	30	12	38	29	10	33.5	32.3	32.3	34.6	33.1	33.3
		1¼	not operational						32.0	32.1	—	32.5	32.4	32.7

TABLE 3

HEAT DISSIPATED AND SURFACE TEMPERATURE OF HEATED PAVEMENT, DECEMBER 25, 1969, SNOWSTORM

Date and Time	Air Temperature (deg F)	Pipe Diameter (in.)	Heat Dissipated by Pipe Spacing (Btu/sq ft)						Surface Temperature by Pipe Spacing (deg F)					
			Portland Cement Concrete			Bituminous Concrete			Portland Cement Concrete			Bituminous Concrete		
			6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.
12-25-69 11:15 p. m.	27.4	¾	132	76	31	81	—	21	33.7	30.3	29.4	33.6	30.6	30.4
		1	87	49	18	96	62	20	32.4	29.5	29.0	34.2	30.5	29.3
		1¼	144	63	24	101	30	10	33.3	31.6	—	34.0	—	29.9
12-26-69 10:05 a. m.	34.4	¾	105	60	26	50	—	15	34.6	32.6	32.3	36.5	32.1	32.6
		1	72	42	13	69	46	35	33.2	32.3	32.1	36.6	33.3	32.7
		1¼	115	51	19	—	19	6	33.7	32.5	—	36.0	33.5	33.6
12-28-69 11:00 a. m.	37.2	¾	46	42	17	33	—	11	47.2	33.2	34.5	38.4	35.6	33.1
		1	43	31	11	46	30	10	39.0	34.0	32.2	37.1	34.8	32.9
		1¼	17	24	7	34	9	2	47.0	33.6	—	36.8	34.1	33.0
12-29-69 9:30 a. m.	34.8	¾	33	30	15	12	—	7	43.8	38.0	31.8	36.5	32.9	31.4
		1	34	26	9	21	22	6	40.8	31.7	30.6	44.2	—	31.4
		1¼	36	30	11	48	18	6	43.8	39.8	—	42.4	34.2	31.5

TABLE 4

HEAT DISSIPATED AND SURFACE TEMPERATURE OF HEATED PAVEMENT, FEBRUARY 16, 1970, SNOWSTORM

Date and Time	Air Temperature (deg F)	Pipe Diameter (in.)	Heat Dissipated by Pipe Spacing (Btu/sq ft)						Surface Temperature by Pipe Spacing (deg F)					
			Portland Cement Concrete			Bituminous Concrete			Portland Cement Concrete			Bituminous Concrete		
			6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.
2-15-70 3:30 p. m.	36.0	¾	97	62	29	44	—	18	33.7	32.6	32.5	34.6	33.1	32.9
		1	54	30	13	46	32	1	32.5	32.2	32.2	34.2	32.6	33.0
		1¼	not operational						32.0	32.0	—	32.4	32.3	32.6
2-16-70 1:30 a. m.	33.4	¾	81	54	25	35	—	14	32.6	32.9	32.7	35.5	33.8	33.8
		1	52	30	12	38	29	10	33.5	32.3	32.3	34.6	33.1	33.3
		1¼	not operational						32.0	32.1	—	32.5	32.4	32.7
2-16-70 1:15 p. m.	36.5	¾	12	25	15	35	—	14	49.5	45.0	43.9	37.0	35.2	35.6
		1	28	21	9	22	22	7	46.4	33.0	32.8	40.2	35.2	34.5
		1¼	not operational						32.1	34.3	—	32.6	33.2	32.9
2-16-70 10:15 p. m.	29.9	¾	115	76	41	92	—	30	36.0	32.9	31.0	32.8	30.2	30.1
		1	46	29	13	28	22	7	31.5	28.8	28.2	32.0	28.5	29.1
		1¼	not operational						28.6	28.8	—	29.2	26.0	28.0
2-17-70 10:45 a. m.	37.1	¾	not operational						36.1	36.4	34.5	36.0	38.0	32.7
		1	26	21	9	16	17	6	45.1	38.1	32.7	38.0	40.3	35.8
		1¼	not operational						31.4	33.3	—	31.1	31.9	32.0

Table 3 gives the heat dissipated and surface temperature during the snowstorm beginning December 25, 1969. The large variations in the heat dissipated per square foot of surface pavement can be attributed to several factors including surface condition (snow-covered, wet, or dry), air temperature, and amount of sunlight incident on the pavement surface.

Table 4 gives the heat dissipated and surface temperature during the snowstorm of February 16, 1970. Again, there are large variations in the amount of heat dissipated.

The temperatures of the fluid of the 3 heat exchangers for the dates and hours of operation are given in Table 5.

TABLE 5

TEMPERATURE OF HEAT EXCHANGER FLUID

Date	Hours of Operation	Temperature (deg F)		
		Heat Exchanger 1	Heat Exchanger 2	Heat Exchanger 3
12-25-69	2	52.0	52.0	49.0
12-29-69	71	46.0	48.0	46.0
1-6-70	80	47.0	47.0	46.0
1-7-70	102	45.0	45.0	44.0
1-13-70	130	43.0	43.0	42.0
1-21-70	140	44.0	43.0	—[a]
1-23-70	160	42.5	42.0	—[a]
2-15-70	170	42.0	41.0	—[a]
2-16-70	200	42.0	40.0	—[a]

[a] Not operational after 1-13-70 due to minor leak at a valve.

Figure 13 shows temperature data of the existing soil 40 ft from the closest heat exchanger.

Figures 14, 15, and 16 show the variation in soil temperature at depths of 3, 7, and 11 ft for heat exchangers 1, 2, and 3 and the control section. The soil temperature of heat exchanger 3 (no insulation) shows a gradual increase after operation was discontinued on January 13, 1970.

Figure 17 shows the soil temperature above and below the 8-in. layer of insulation located above heat exchanger 2. At first it would appear that 8 in. of insulation has little effect on the soil temperature at a depth of 3 ft; however, consideration must be

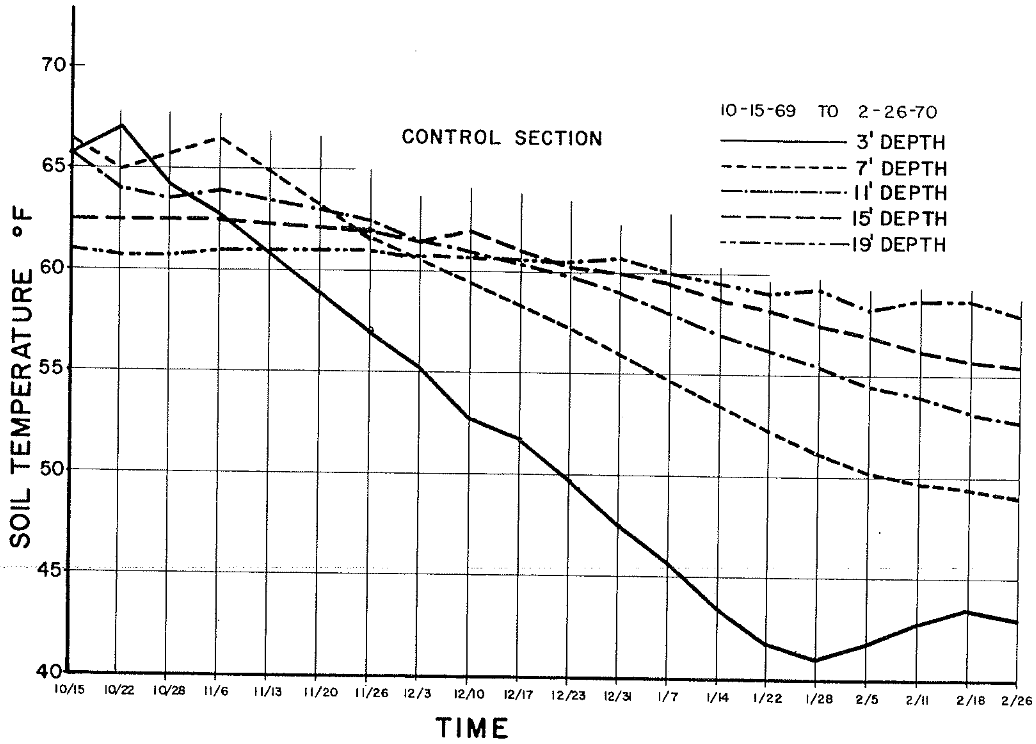


Figure 13. Temperature of existing soil at depths of 3, 7, 11, 15, and 19 ft.

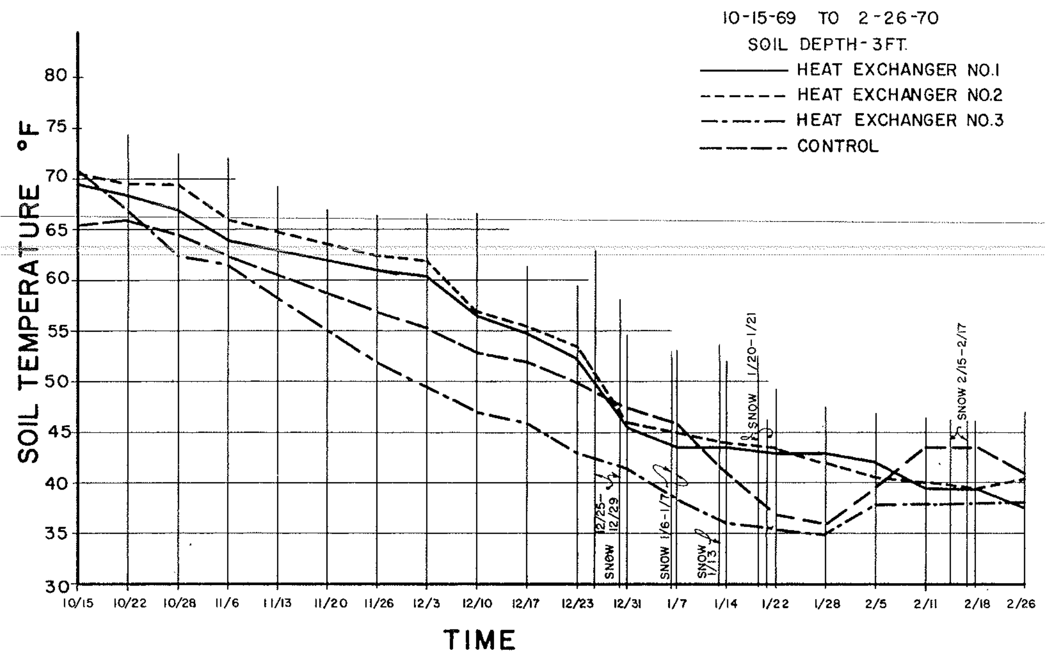


Figure 14. Soil temperature of heat exchangers at depth of 3 ft.

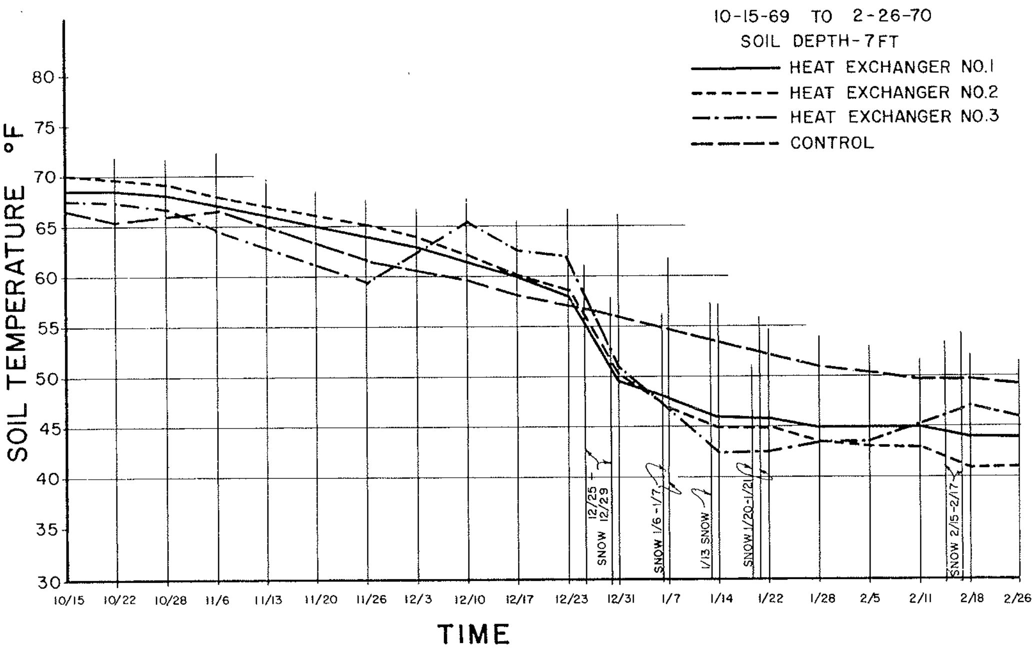


Figure 15. Soil temperature of heat exchangers at depth of 7 ft.

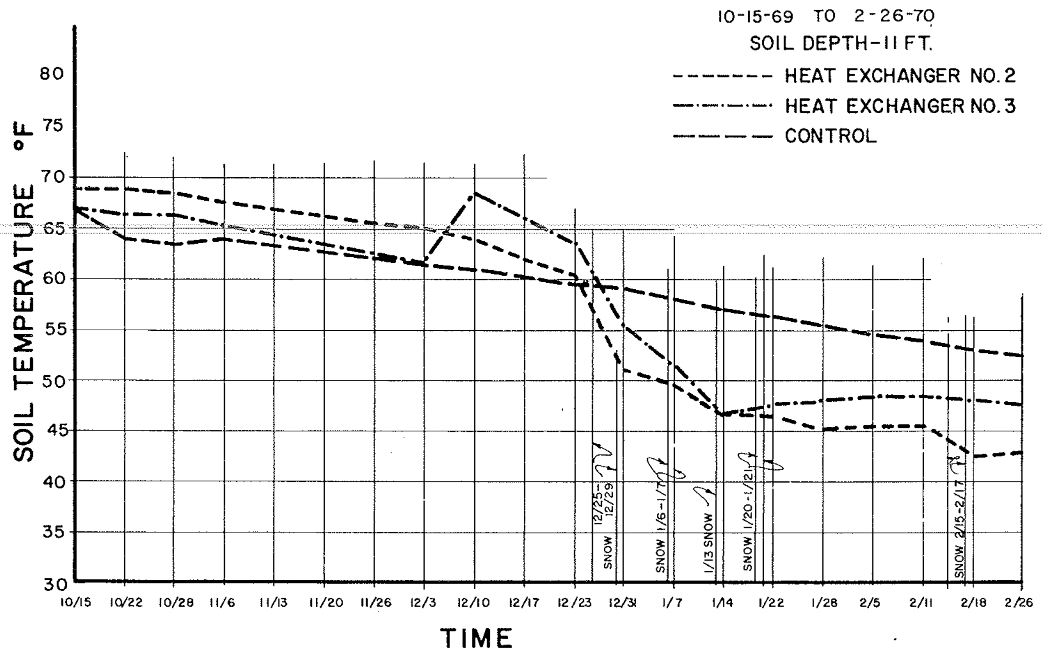


Figure 16. Soil temperature of heat exchangers at depth of 11 ft.

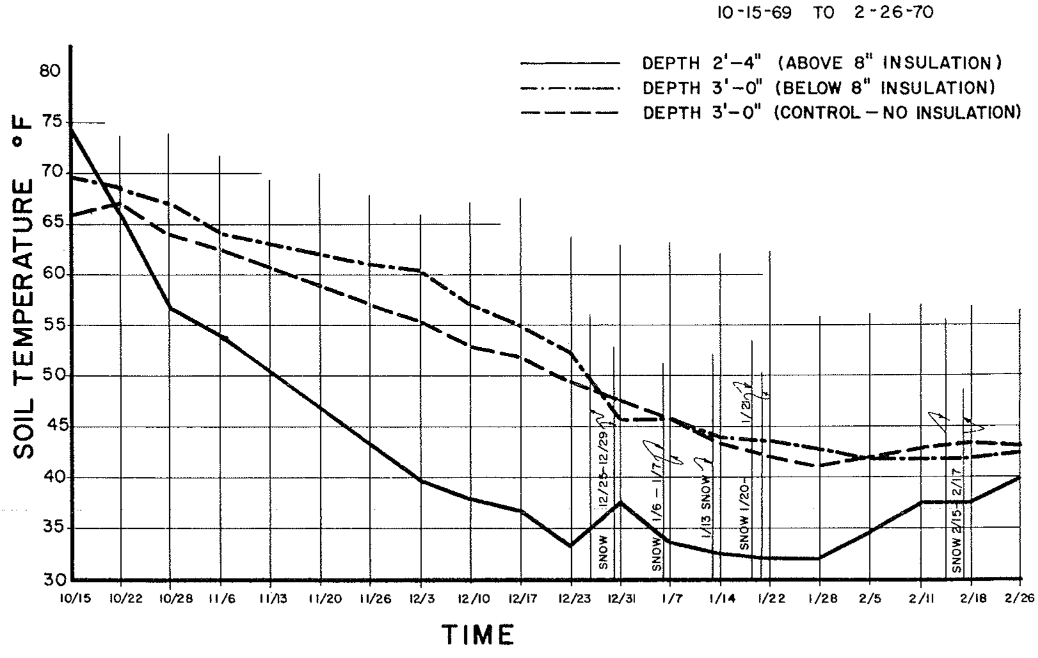


Figure 17. Soil temperature above and below 8 in. of insulation.

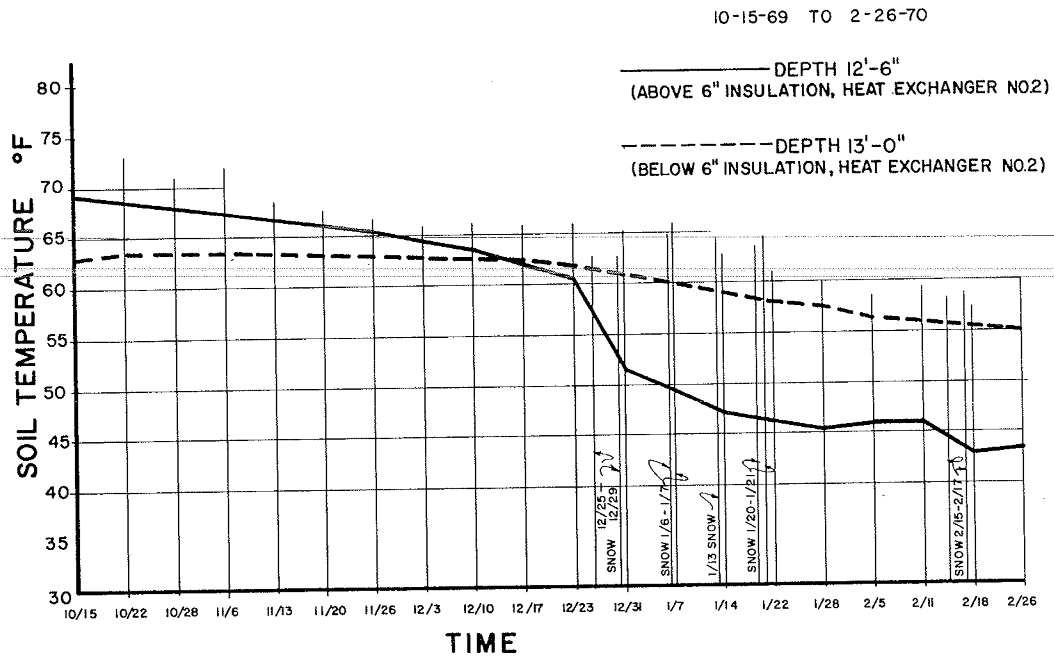


Figure 18. Soil temperature above and below 6 in. of insulation at a depth of 13 ft.

given to the fact that heat exchanger 2 extracted considerable heat during 200 hours of operation.

Figure 18 shows the effect of the 6-in. layer of insulation below heat exchanger 2. The insulation appears to be very effective in restricting the flow of heat as can be seen from the 10 F temperature differential after heat exchanger 2 was first put in operation on December 25, 1969.

CONCLUSIONS

1. The following combination of factors was found to be an effective means for melting snow and ice on pavement surfaces: (a) wrought iron pipes embedded at a depth of 2 in. in portland cement concrete; (b) spacing of pipes on 6-in. centers; (c) nominal diameter of wrought iron pipes of $^3/_4$ to $1^1/_2$ in.; (d) temperature of the heating fluid in the range of 42 to 52 F; and (e) air temperature above 15 F.
2. This combination of factors produced approximately 100 Btu/sq ft of pavement.
3. Based on the amount of heat dissipated per square foot of pavement, under identical conditions, the thermal conductivity of the portland cement concrete, as used in this experiment, was twice that of the bituminous concrete.
4. The use of pipes buried in the earth can be an effective means of extracting sufficient heat for use in melting snow and ice on pavements.
5. For this particular experiment, the rate of heat extracted from the earth by 1 ft of $1^1/_4$-in. wrought iron pipe was approximately 22 Btu/hr.
6. The use of 2 in. of insulation directly below a portland cement concrete pavement was not an effective means of improving the efficiency of embedded heating elements. Insulation restricted the natural flow of heat from the subbase to the pavement such that the rate of snow melting on the insulated portion of the heated pavement was not as rapid as on the uninsulated portion.

Informal Discussion

Don L. Spellman

Do you have any measurements to indicate what percentage of the heat sink capacity was used up during each storm period? In other words, how many times can you repeat this?

Winters

We do not know the limits yet; we operated only 200 hours, and it was still melting snow successfully. We do have temperature measurements of the soil, and we can tell when the system is operating because we can see a distinct drop in the soil temperature.

Spellman

Was the volume of the heat sink that you had big enough to take care of one winter's operation?

Winters

Yes.

Samuel H. Nitzberg

What was the water table?

Winters

When we excavated it was greater than 14 ft, but later it came up to 3 ft or so.

Lawrence H. Chenault

For about 5 years now we have been using thin-walled polyethylene pipe for snow-melting systems with no problems at all, but we really have not had an opportunity to get a direct comparison of the performance of the plastic versus that of the metal. Do you have any comments on that?

Winters

In our system the plastic is definitely not as effective as the metal, but that is mainly because the temperature of the fluid we are using is very low. The lower thermal conductivity of this plastic pipe requires a higher flow of heat. If we were using temperatures up around 100 F, I think the effect of the decreased thermal conductivity of the plastic pipe would be negligible.

Chenault

The limited tests that we did run were a comparison of copper pipe and plastic, and we determined that the major factor in heat transfer ability of the total system was dominated by the concrete wall around the pipe and that the coefficient of thermal conductivity of the 2 pipe materials became insignificant in this whole system.

Winters

Normally it would if you are using temperatures higher than what we were using. Above 100 F, the limiting factor is the thickness of the concrete and its thermal conductivity. For our low temperature system, the lower thermal conductivity of the plastic pipe reduced its heat output by half that of a comparable wrought iron pipe.

Chenault

I am talking about 130-deg water temperature.

Winters

Then it would probably have no effect.

Guenther E. Frankenstein

I think you said your operating cost was 45 cents/sq ft. How does this compare with the cost of a direct electrical heating system such as the one Dave Minsk is working on at USACRREL? And also, how do you account for the lack of effectiveness of the bituminous concrete? You apparently had some sunny days that should have warmed the black surface; so there should have been melting from both directions, yet there was none.

Winters

Yes, the blacktop would normally pick up the radiation from the sun, but when it is covered with snow it reflects it. The thermal conductivity of the bituminous concrete, from the measurements we made, is only half that of portland cement concrete. As for the cost, that 45 cents/sq ft was based on a 5-year record for an electrically heated system, which has nothing to do with the present system. Approximately half of that cost is the demand charge by the utility company. We paid several thousand dollars just to have electricity there whether we used it or not. The other half is the cost of operating the system. I do not know how this compares with the costs of the system Dave is working on.

Frankenstein

I would disagree with your statement that when the blacktop is covered with snow it would not pick up the radiation. You are talking about 1, 2, or 3 in. of snow cover. We have found in tests in Alaska that with the same amount of snow at your temperatures it would still have an effect.

Winters

From our observations, the amount of solar radiation picked up by the blacktop when covered with snow is negligible.

David Minsk

I think it is awfully difficult to make any comparisons of cost in experimental installations. They are not representative of an actual installation because of so many variables. The cost of operation, for instance, of our installation was not tallied to as precise an extent as that of Frank Winters'. We operated it for only 2 years, and in that time we did not evaluate the actual cost; but we do know the number of watt-hours required. I do not recall the figures offhand, but I would say they were on the order of magnitude of the New Jersey tests in spite of the heavier snowfall that we had because of the more rapid placement of the thermal energy right where it was needed—at the interface. We did not have to contend with the increased thermal conductivity of the 1, 2, or 3 in. of pavement placed between the heating elements and the surface.

Winters

I want to mention that the 45 cents/sq ft was for the operation of the system that was constructed in 1964. For the present installation we do not have any accurate figures on cost, other than that the cost of heating the area by the pipes is about $^1/_{100}$ that of melting the snow electrically because all we have to do is run three $^1/_4$-hp pumps compared to using 50,000 to 100,000 watts.

Spellman

Next summer you should be able to store some solar energy. What temperature do you expect to get compared to the 52 F you were speaking of?

Winters

The temperature of the pavement should reach 120 F for the bituminous concrete. We have already noticed that on a sunny day the temperature of bituminous concrete at a depth of 2 or 3 in. is 10 to 20 deg higher than that of the portland cement concrete. I do not know whether the heat sink will get to 120 deg, but I would expect it to be at least 30 deg higher than the natural soil temperature.

Chenault

I have one comment on operating cost based on our experience in snow melting. If gas fuel at 8 cents/therm (a therm is 1,000 Btu) and an operating time of 150 hr/yr are used, the annual operating cost would be about $20/1,000 sq ft.

James E. Bell

Did I understand that you did not turn the system on until after it had snowed. Why was this?

Winters

On Christmas it snowed and again on Easter, and because all the roads in New Jersey are not heated it took some time to get to the installation. Once we did turn the system on several hours ahead of time, but generally it always happened to snow when no one was available to turn it on.

Bell

Was there any difference in the effect when you had it on earlier?

Winters

The one time when it was turned on before the snow fell, we got a total accumulation of 3 in.; but in the one area where the system was operating, we got a maximum of 1 in. and that soon melted. It depends so much on temperature at the time that I could not say for sure. Yes, it is always better to have it on ahead of time.

Thad M. Jones

Would it be possible to replace all that excavation with something like a cesspool and use that as a big heat sink? How would the size of that compare with the ethylene glycol system?

Winters

You could use a number of different types of reservoirs. Even city water at 50 F could be used and run through the pipes. Sufficient data do not now exist to make size comparisons of the various systems.

M. E. Volz

I have three questions. First, how do you get Christmas off? Second, how do you get Easter off? And third, do you think that a part of your conclusion may be invalid? My reason for asking that question is that we have quite an elaborate electrically heated strip at O'Hare Field. Air temperature does not really seem to affect it nearly as much as wind velocity, dew point, and temperature. As a matter of fact, with regard to the 42-deg water you used, I will guarantee that, at 30 deg with a few degrees spread in the dew point and a fairly substantial wind, the entire thing will be frozen solid. I think the chill factor is far more important than the outside temperature. Do you have any comment on that?

Winters

We do not have any means for measuring wind velocity at our installation. All we can do is measure the air temperature. The reason I said 20 F is that one time as the snow was coming down we melted it, but then, as the temperature dropped below 20 F, it refroze except in certain spots. It had melted directly above the pipes and that froze. It had not melted in between the pipes, and that snow was blown away by the wind. We had the unusual situation of ice above the pipes and clear pavement between.

Nitzberg

These are some figures I have put together for one mile of runway, 150 ft wide by 5,200 ft long, or an area of 780,000 sq ft. With a load of 156 million Btu and using 2 high pressure hot-water boilers having a 75 million Btu output, we can operate 1 hour on 600 gal of No. 4 fuel at 9 cents/gal or $54/hr and guarantee to melt snow within 2 hours.

Lorne W. Gold

It is a little difficult to compare those figures with those that have been presented.

Winters

The 2 installations that we have at the New Jersey Department of Transportation are electrically heated and they are expensive—we are well aware of that. A boiler would be quite a bit cheaper than electrical heating, as you say. In fact our system is designed for a boiler as the next stage. However, the point of this research is to find out whether we can do it with the heat of the earth, which costs nothing.

Gold

From the study you have carried out, is it possible to get some design information on the amount of heat lost into the ground? Can you comment on the advantages of putting insulation under the system to cut down the heat loss into the ground?

Winters

We do have some data available. They are not contained in this report, but we do have temperature data for the surface of the slab and every 2 in. all the way through both the portland cement concrete and the bituminous concrete slabs. So we probably could determine how much heat is lost into the ground from the subbase and base courses. With regard to the insulation, it did not seem to be effective in any way in reducing the heat losses. Apparently there was sufficient heat in the ground to come up through the portland cement concrete slab to melt a little of the snow anyway. The area electrically heated at 20 W/sq ft melted snow just as well as the area electrically heated at 40 W/sq ft where there was a layer of insulation below it. So we found that the insulation was not helping at all.

Minsk

I might comment on some aspects of heating pavements that may not have shown up in the New Jersey work where low temperature fluids were used. If you do use a high temperature fluid to reduce the spacing of pipes and reduce the amount of installation required, there is the requirement for fast response of a higher temperature fluid. The higher the temperature is the better, you might think, because of increased heat transfer and other factors; but thermal stresses that are developed have been shown to increase the deterioration of pavement. This was shown in tests made at Loring Air Force Base several years ago. An installation was so badly broken up from thermal stresses from heat production that the installation had to be abandoned. Low temperature systems, of course, have other drawbacks, but certainly not that of deteriorating the pavement due to thermal stress cracking.

Control of Road Snow and Ice by Salt and Electrical Road Heating

Leonard H. Watkins

The normal treatment for control and removal of snow and ice from roads in the United Kingdom is the application of sodium chloride, usually in the form of rock salt. The efficiency of this method depends on whether salting-lorry crews get into action at the correct moment; in addition, reliable ice warning devices are needed. This paper briefly reviews present salting practice and work being done to develop suitable ice warning equipment. It also gives an account of the development of an inhibitor to the corrosion of steel in automobile bodies caused by sodium chloride. The cost of this corrosion in the United Kingdom is many times greater than the cost of adding a corrosion inhibitor, if a suitable one can be found. A feasible, although expensive, alternative to using salt is to employ electrical road heating. This paper discusses work done at the Road Research Laboratory on the design and specification of these systems and gives some practical experience with their use in the United Kingdom.

Chemical treatment of roads and road heating for control and removal of snow and ice have become very widely used in the United Kingdom in the past 10 years. British winters are not so severe overall as those of, for example, Canada or the Scandinavian countries, and the winter of 1962-63, when land in the English lowlands was under snow for about 60 days, was the coldest in over 200 years. However, the rapid fluctuations in temperature and weather that can take place in the United Kingdom bring their own difficulties, and the organization and equipment required for winter maintenance are increasing rapidly in cost and complexity to keep the increasing traffic flowing satisfactorily. The considerable use of sodium chloride (normally in the form of rock salt) has also brought other problems due to its corrosive nature. This paper discusses the weather conditions in the United Kingdom that require treatment, and outlines the way that the problems are being tackled by research and development.

WEATHER CONDITIONS REQUIRING TREATMENT

The commonly occurring conditions requiring treatment are snow; ice films formed when a road surface, wet by rain or dew, cools below the freezing point; and hoarfrost, which consists of small crystals of ice deposited when the surface is cooled by radiation to a temperature below the frost point of the air. Less frequently, glare ice may be formed by rain on a surface at a temperature below 0 C.

Snow

The occurrence of snow is recorded by meteorological observers, and information on the amount of precipitation and the temperature at which it occurs is available from daily weather records of the Meteorological Office.

Data extracted from the records for the period from October 1962 to March 1965 for London Airport are given in Table 1. Quantity of precipitation is expressed as an equivalent depth of water so that, taking the density of snow to be about 100 kg/m^3, 10 mm of snow is equivalent to 1 mm of water. The air temperatures during snowfall were rarely below -1 C and on the majority of occasions were above freezing point.

TABLE 1

AMOUNT OF PRECIPITATION AND AIR TEMPERATURE RECORDED DURING SNOWFALL AT LONDON AIRPORT, OCTOBER 1962 TO MARCH 1965

Amount of Precipitation as an Equivalent Depth of Water (mm)	Number of Observations at Different Air Temperatures (deg C)										
	4	3	2	1	0	-1	-2	-3	-4	-5	-6
0.1		1	2	1	1						
0.2					2			1			
0.3				1		1					
0.4				1	1	2			1		
0.5											
0.6		1	1	1	1						
1.0			2	2	2	1					
2.0	1	1		2	3						
3.0				1			1				
4.0			1		3	1					
5.0	1		1								
6.0						1					

Coatings of Ice

There is a lack of recorded information on the temperatures of road surface during icy conditions, but an indication of the probable range is given in Table 2. The table gives the frequency with which minimum temperatures in various ranges were recorded and when icy roads had been forecast and salt was applied as a precautionary measure. Temperatures were usually above -2 C but were down to -4 C on 4 occasions.

Hoarfrost

Hoarfrost is not often seen on roads with substantial thicknesses of construction, which, because of their thermal characteristics, cool more slowly than their surroundings. The vapor content of the air is depleted mainly by deposition on the colder surfaces of vegetation, which develop thick coatings of frost. However, appreciable deposits sometimes form on roads of lighter construction and on bridge decks, which cool more quickly because of heat loss from their lower surfaces.

There is a short period after dawn when high thermal conductivity has an adverse effect, and conditions appear to favor frost formation on the road. At this time the temperature of the surrounding vegetation may be rising quickly, releasing water vapor that can condense on the cooler road. The period during which these conditions exist is brief but may account for the suddenly occurring phenomenon sometimes termed "flash icing."

Frost quantities on roads have not been measured, but measurements of deposits formed in a cold room and having a similar appearance to those on the road indicate that the range from slight to heavy corresponded to equivalent water depths from 0.01 to 0.15 mm. There is, however, no obvious relationship between the amount of deposit and the atmospheric conditions recorded.

Salt-treated roads are often wet when neighboring untreated roads are dry. This is because of condensation induced by the presence of salt. This condensation usually occurs at sunrise when temperatures are rising, but may sometimes begin soon after treatment early in the night. Again the quantity is limited by heat exchange processes, and in practice there does not appear to be any risk of brine becoming so diluted that it freezes when the temperature falls to a lower level.

TABLE 2

FREQUENCY AND LEVEL OF MINIMUM TEMPERATURE RECORDED ON MOTORWAYS WHEN THE ROAD WAS SALTED

Minimum Temperature Range (deg C)	Frequency Recorded	Minimum Temperature Range (deg C)	Frequency Recorded
3 to 4	2	-1 to 0	10
2 to 3	1	-2 to -1	9
1 to 2	9	-3 to -2	6
0 to 1	9	-4 to -3	4

Glare Ice

This form of ice occurs when rain falls on a surface with a temperature below freezing. The rain may be supercooled and partially freeze on striking the ground so that dangerous conditions develop very quickly. Meteorological conditions that cause extensive glare ice are rare over Britain, but they probably occur a number of times each year in limited areas. Instances were recorded in the vicinity of the Road Research Laboratory at Harmondsworth in 1964 and 1966. Both occurred between 7:00 and 8:00 a.m., and air temperatures recorded at the time were -3 C. On such occasions the ice may be quite thick, perhaps up to 30 mm.

CHEMICAL TREATMENT

Undoubtedly the major development in winter maintenance in the United Kingdom has been the rapid increase in recent years in the use of rock salt for the prevention of ice formation on roads and for facilitating the removal of snow.

Recommendations on the use of chemicals were issued by the Road Research Laboratory as long ago as 1941, but this method of treatment did not begin to be generally applied until the mid-1950's. Since that time there has been a sixfold increase in the amount of salt used, and recommended methods of treatment, taking into account the developments that have taken place in equipment, have been published as a Road Research Laboratory Road Note (1), from which the following paragraphs are summarized extracts.

Salt is most effective when applied early in the potential development of icy conditions. At this stage the quantity of ice to be prevented or cleared, and therefore the quantity of salt required, cannot be known. Furthermore, in certain circumstances, the rate of clearing has to be considered, and this may depend on factors not easily assessed beforehand. The treatments recommended are therefore based on the application of standard quantities that will be adequate in average conditions; more severe weather, or the need for more rapid clearing, will entail repeated applications. Modern equipment will effectively spread the quantities of salt recommended, without mixing the salt with abrasive.

When forecasts of icy conditions can be obtained from meteorological stations or from local observations, salt may be spread on heavily trafficked roads as a precautionary measure before any ice actually forms. Such forecasts will inevitably be incorrect on occasions, but the resulting wastage of salt may be partly offset by the smaller quantities required when icy conditions do develop later. The practice is justified on motorways by the virtual elimination of the occurrence of ice.

Thin films of ice formed by the freezing of water on the road surfaces are usually less than 0.25 mm thick, which is equivalent to approximately 0.25 kg/m^2 of ice. The temperature during periods of icing is usually above -3 C, so that an application of 15 g/m^2 of common salt is sufficient to effect complete melting. Application of this quantity before the onset of freezing will prevent the formation of ice.

When ice has formed, 15 g/m^2 of salt will not be sufficient to bring about the required increase in skidding resistance in a reasonable time and 50 g/m^2 should be applied.

The density of fresh untrafficked snow is about one-tenth that of ice, that is, about 90 kg/m^3; a 1-cm depth of snow is therefore roughly equivalent to 1 kg/m^2 of ice.

In practice, it is found that one-half of the quantity of common salt required for complete melting will reduce the snow to a state in which it can be dispersed by traffic, and about 6 g/m^2 of salt is required per 1 cm of fresh snow for each degree centigrade that the air temperature is below the freezing point. When snowfalls of 1 cm or more occur, the temperature is usually higher than -3 C and 1 or 2 applications of salt at 50 g/m^2 will be sufficient to clear the average fall. The quantities of salt required for the treatment of 1 km of a 7.3-m wide roadway are about 100 kg at 15 g/m^2 and about 360 kg at 50 g/m^2.

Every effort should be made to ensure by the prompt application of adequate amounts of salt that thick layers of hard-packed snow and ice do not form on the roadway. If such layers do form and are no thicker than about 25 mm, their removal is possible at temperatures above about -5 C by applying salt at 5 times the rate required for the same depth of fresh snow. When the layer is considerably thicker than 25 mm or the temperature is low, application of salt is inadvisable, because the accumulation of salt solution in the depressions will produce a very uneven and slippery running surface.

In these circumstances abrasives may be spread to make the surface less slippery. The amount of abrasive required ranges from 100 to 400 g/m^2 of road surface. The addition to the abrasive of about $^1/_{30}$ of its weight of salt will prevent the abrasive particles from freezing together and will help them penetrate the surface of the hard snow or ice.

FORECASTING FOR PRECAUTIONARY TREATMENT

Forecasts of snow and icy roads are issued by the U. K. Meteorological Office to assist engineers responsible for maintenance in making arrangements for snow clearing and chemical treatment. These warnings are transmitted during normal working hours to enable maintenance crews to be alerted and equipment prepared. However, forecasts made perhaps many hours before icy conditions are expected to develop may not prove accurate, and they are revised periodically throughout the night so that, where a night shift is worked, action can be delayed until conditions become more certain.

Road temperatures are frequently only a degree or two below freezing point when ice forms, so that the margin of error in forecasting these temperatures is small. Moreover, whether ice forms often depends on the rate at which the road dries, and this is determined by factors, such as drainage and amount of traffic, that the forecaster cannot take into account.

As far as is known, no research is currently being undertaken on the forecasting of icy conditions on roads. During the past year, several papers have been published on the night minimum temperatures of roads or of concrete slabs. Three papers (2, 3, 4) were concerned with the relationship to night minimum air temperature and showed that the latter was about 1 C higher in the winter months. Thus techniques for forecasting night minimum air temperature can be extended to the forecasting of minimum road temperature. Another paper (5) on minimum road temperatures was based on the temperature of the surface at 1800 G. m. t. the previous evening and the mean cloud cover during the night. Further work is being based on the surface temperature at 1200 instead of 1800 G. m.t.

ICE WARNING DETECTORS

Local measurements of road conditions may provide a more reliable guide for maintenance staff than meteorological forecasts. Devices that measure road temperature and wetness are now available, and trial ice warning installations have been set up in Britain and elsewhere in Europe. These devices measure road temperature by means of an embedded probe and detect wetness by the decrease in electrical resistance between electrodes in the road surface. Signals from the detecting elements are combined to give an alarm signal when icing conditions develop. Advance warning for precautionary treatment can be obtained by setting the critical temperature a degree or more above freezing point, although, naturally, the higher the temperature is set the greater will be the likelihood of a false alarm. Table 3 gives the amount of warning and frequency of false alarms obtained with various temperature settings of a prototype warning device tested at the Road Research Laboratory.

The onset of snowfall may be detected by using a second pair of electrodes separated by a surface that is heated to melt the snow and give a moisture signal. Figure 1 shows a commercial arrangement of temperature, wetness, and snow sensors to be placed in the road surface. The left circular element is the snow sensor, the right one is the moisture sensor, and the block between them contains the temperature sensor.

Many false warnings can be given by this simple device when moisture condenses on the road only because of the presence of salt remaining from a previous treatment. By using a third pair of moisture electrodes in a concrete block near the road but free from salt, this ambiguity can be resolved.

TABLE 3

AMOUNT OF WARNING AND NUMBER OF FALSE ALARMS GIVEN BY VARIOUS TEMPERATURE SETTINGS OF AN ICE WARNING DEVICE

Alarm Temperature Setting (deg C)	Frequency Recorded (percent)						
	Amount of Warning (h)						False Alarms
	<½	½ to 1	1 to 1½	1½ to 2	2 to 5	>5	
1.5	0	10	9	17	27	6	31
1.0	4	23	17	10	18	2	26
0.5	25	41	13	4	6	0	11

If the moisture deposit on the road is not created merely by the hygroscopic nature of the salt but is due perhaps to slight drizzle, there may nevertheless be enough salt remaining from a previous treatment to prevent the formation of ice. A further pair of electrodes placed in the road with an associated trigger circuit set to operate at a sufficiently low resistance can be used to cancel the warning signal.

Hoarfrost cannot be predicted or detected by these sensors just described. A lithium chloride humidity sensor can give an indication of dewpoint or frostpoint, which when compared electrically with the road surface temperature could be used to detect or predict the formation of hoarfrost. A sensor of this type is being developed at the Road Research Laboratory.

Figure 2 shows a suitable interconnection of all the sensors mentioned to give a warning to spread salt. An instrument based on this circuit is now being evaluated at the Road Research Laboratory.

There seems at present to be no way of predicting glare ice by instruments placed in the road, but fortunately this condition is rare in the United Kingdom.

HARMFUL EFFECTS OF SALT TREATMENT

Damage to Roads

Although salt has long been known to accelerate the scaling of concrete by frost action, the factors affecting the resistance of concrete, such as the amount of entrained air, water-cement ratio, and age before treatment, are now also known and there is little evidence in Britain so far of damage to concrete pavements or structures made to modern specifications.

Bituminous surfacings, which are permeable by water, may be damaged by frost, but there is no evidence from the laboratory that the process is accelerated by the application of salt. The only controlled tests of salt treatment on roads appear to be those carried out by Nichols and Price (6) in Cheshire from 1952 to 1956. Comparing adjoining sections of bituminous macadam and surface-dressed roads, they found that salt treatment had no harmful effect and in fact the untreated section suffered greater damage over the period of observation. However, salt modifies road conditions by temporarily lowering the temperature when it is applied to snow or ice, and facilitates the entry of water into structures that would be impermeable when frozen. The possibility that this is sometimes a contributory factor in damage to roads cannot be entirely ruled out. A recent survey (7) of current opinion in 30 counties showed that there was little definite evidence of damage due to salt,

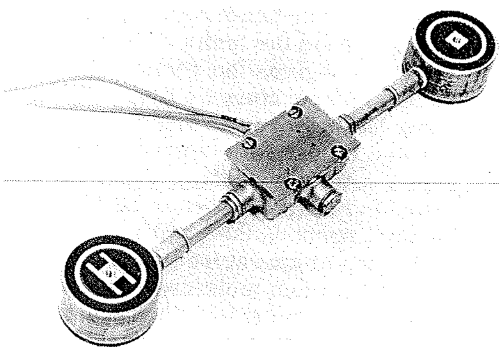


Figure 1. Sensors for detection of snow, low temperatures, and surface moisture.

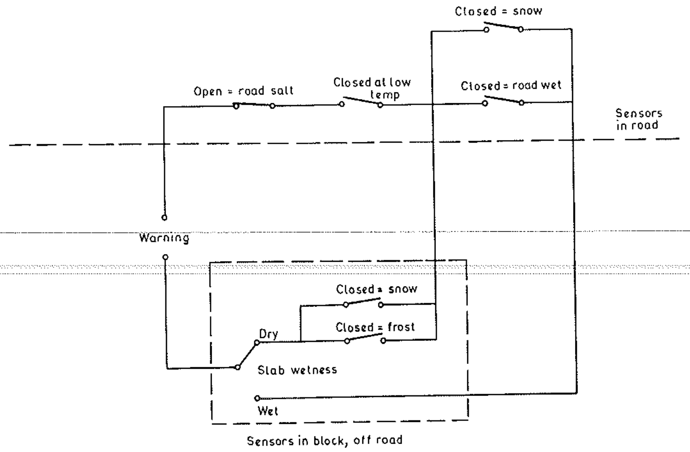


Figure 2. Suitable interconnection of sensors to give warning to spread salt.

although in 9 counties it was suspected of having accelerated the failure of some macadams and surface dressings.

Damage to Vehicles

It is now generally accepted that there is an increase in the corrosion of motor vehicles due to salt. A survey carried out by the Road Research Laboratory (8) has shown that corrosion rates of vehicles are appreciably higher in Derbyshire, where the average amount of salt used annually is about 4,400 kg/km, than it is in Pembrokeshire, where the amount of salt used is negligible. It is estimated for instance that the average life of mufflers in the unsalted area is about 4 years, about double that in the heavily salted area. It we assume that replacement costs £6 and that the general use of salt will be at the higher rates in the main centers of population, increased expenditure due to salting for this component alone amounts to about £1 per vehicle per year, or a total of £14 million per year for the estimated vehicle population in 1970.

The potential benefits of reducing corrosion are therefore considerable, and this fact has stimulated investigations into the use of corrosion-inhibiting agents in several countries.

Motor vehicles come into contact with de-icing salt solutions by splashing and by spray. A range of laboratory tests has been used by different investigators in their evaluations of inhibitors. Unfortunately, in the majority of cases, the conditions existing in the field have not been approximated in the laboratory. The 2 factors most ignored have been temperature and brine concentration.

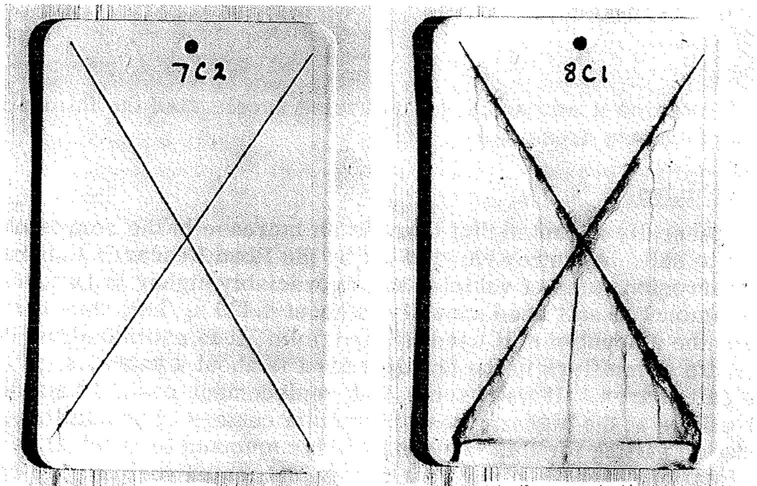
The temperature is important because it governs the rate of the corrosion reaction and can have an effect on the protective action of the inhibitor. This is especially true in the case of film-forming inhibitors. It is surprising that a number of investigators have conducted their experiments at room temperature in the range 20 to 25 C.

Brine concentration also affects the rate of corrosion. It has been shown that brine is most corrosive in the 3 to 6 percent concentration range; above and below this range, the amount of corrosion caused decrease rapidly.

The most commonly applied test for the evaluation of corrosion inhibitors is an intermittent immersion test carried out on bare mild steel panels. Continuous immersion tests are not normally favored because it is considered unrealistic to have inhibitors continuously applied to a metal surface, a condition that would certainly not apply in practice.

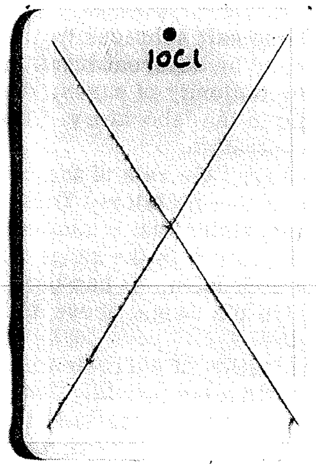
At the Road Research Laboratory we have used an intermittent spray test of 4 hours duration followed by 20 hours at rest, at temperatures of both 5 and 25 C. It has been shown that inhibitors generally appear to be much more effective in reducing corrosion of mild steel when tested under intermittent immersion conditions compared with intermittent spray. It has also been shown that the effect of inhibitors on the corrosion rate of bare mild steel cannot be directly related to the effect on rust creep on phosphated and painted steel that has been damaged with a cross scratch. The addition of 1 percent sodium polymetaphosphate to salt reduces the rate of rust creep from scratch damage to a marked extent for both primers and for complete vehicle paint systems on phosphated steel panels. Under similar intermittent spray conditions the inhibition of bare steel corrosion by sodium polymetaphosphate is extremely small (Fig. 3).

Two inhibitors are being tested in a full scale test track using 7 new small sedan vehicles that were obtained from the British Leyland Motor Corporation. These were standard production vehicles but produced under carefully controlled conditions on the production line in the same batch and were metal pretreated and painted under uniform conditions so that all are equivalent. During the winter of 1969-70 these 7 vehicles were run through 4 separate splash areas containing rainwater, brine, and brine plus



tap water

brine (3 percent rock salt)



brine and sodium polyphosphate

Figure 3. Corrosion test panels.

2 different inhibitors. Motoring at a speed of about 65 km/hr will simulate normal motoring conditions and ensure that corrosive liquids are driven into crevices. The track run is followed by garage storage, which prevents rapid drying out of the vehicles. When a sufficient level of corrosion damage has been developed, the vehicles will be cut open and examined in detail.

ROAD HEATING

In comparison with chemical treatment, road heating is an expensive method of snow and ice control, but its application can be justified in certain limited areas where failure to treat the road quickly can result in a disproportionate degree of traffic dislocation and create jams that make treatment by conventional methods impossible. Such areas are gradients approaching intersections, elevated roads and underpasses, and sharp bends and roundabouts.

Heating overcomes the problem of snow disposal on elevated roads where space limitations do not permit the storage of snow at the roadside. The fact that the question of damage to reinforced concrete by de-icing salts is as yet unresolved is an additional reason for protecting elevated structures by this method.

The Road Research Laboratory began experiments in 1956 with a small installation at Harmondsworth, Middlesex, in which 2 types of heating element were used: (a) PVC-insulated resistive wire elements operating at medium voltage (240 V) and (b) uninsulated expanded steel mesh carrying comparatively high currents at extra low voltage (55 V). Many installations of both types are now in operation, ranging in size from the 8-MW scheme on the elevated Chiswick-Boston Manor section of the M4 motorway, to installations of a few kilowatts on service ramps.

Operation of the Harmondsworth experimental installation at various levels of output and measurements of heat transfer made on this and other installations provided the basis of a method of relating the heat requirements to weather conditions (9).

Roads at Ground Level

Two weather conditions were considered: (a) clear nights, with strong radiation leading to ice formation, and (b) overcast skies and high winds, in which the installation might be called on to melt snow. Under clear skies it was found that the maximum heat transfer, Q (in W/m^2), from the surface could be expressed by the equation

$$Q = 90 + (11.9 + 1.69u)(T_s - T_a) \qquad (1)$$

where T_s is the temperature of the surface in deg C, T_a is the temperature of the air in deg C, and u is the wind speed in mph. In overcast conditions when the heat transfer is mainly due to convection and evaporation the equation becomes

$$Q = (11.9 + 1.69u)(T_s - T_a) \qquad (2)$$

In which of these 2 conditions the greater heat loss occurs depends on the nature of the site. On an urban installation sheltered from high winds, maximum heat loss probably occurs with clear skies, while on an exposed site it may be greater in the higher wind speeds and lower air temperatures associated with snow.

Elevated Roads

Measurements on British installations have shown that, when the road is in contact with the ground, heat flow downward from the elements is negligible after it has been in operation for a few hours, and no allowance is made for it in calculating heat requirement. For installations on elevated roads, an allowance is necessary to compensate for the heat lost by convection and radiation at the lower surface, which must be added to the values given by Eq. 1 or 2 for the upper surface.

The equation relating this heat loss to weather conditions, derived from measurements on elevated structures, is

$$Q_1 = (3.8 + 1.69u)(T_1 - T_a)$$

where T_1 is the temperature of the surface in deg C.

Practical Experience

The following conclusions have been drawn from an examination of the performance of heating schemes (10):

1. The power required is 100 to 130 W/m^2 (9 to 12 W/ft^2) for sheltered sites rising to 150 to 200 W/m^2 (14 to 19 W/ft^2) for exposed sites;
2. Installations using uninsulated steel mesh as the embedded conductor at extra low voltage have been found in general to be more reliable than installations using cable at a higher voltage;
3. The estimated capital cost in 1968 was about £4.6/m^2 and the average annual operating cost was about £0.15/m^2 for both types of installation; and
4. The costs of electrical road heating are about 30 times the cost of using rock salt, and local circumstances must be unusual and critical to justify this high cost.

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Informal Discussion

Glenn G. Balmer

You said that the cost of heating was about thirty times that of salt. Are you referring to electric heating, or are you considering heating by methods other than electric heating?

Watkins

I am considering electric heating only. There are few road installations with other forms of heating in the United Kingdom. Frankly, I am not particularly familiar with them, and I do not think there are likely to be very many.

John Pendleton

I very much appreciate your approach of anticipating storms and getting out on the highway ahead of time with chemicals. We would like to do that, but we generally cannot because the weather is continuously so poor. We do call crews out ahead of time. I am also interested in your early warning system. Do you have problems with keeping the salt on the highway before the precipitation starts, or does traffic tend to whip it off?

Watkins

This is one of the reasons why we use a fairly coarse material. We have experimented with different gradings. Somebody said earlier that in parts of Europe they used a very finely ground salt; we do not. We find that with the amount of warning we can get and the grading of the salt that we use, we do not have much trouble with this. At some places—the Severn Bridge for example—urea is used because of the corrosivity of salt and this is put down in a fine powder form. Owing to the high winds at this site, it blew off the bridge into the Bristol Channel and they had to combine it with a quantity of grit to give it some weight. Of course, it is more difficult for us to achieve our ideal of preventing ice formation in an urban area. The salting vehicles become snarled up with traffic and so on. It is much easier to achieve the ideal under the motorway conditions I have talked about.

John P. Wilmot

Have you used any plastic blades in place of rubber? In Europe, they call it Vulkollan.

Watkins

I do not know of any.

Liquid Treatments of Commercial $CaCl_2$ in Winter Road Maintenance

G. E. Scotto

This paper describes 2 experiments using liquid solutions of a commercial calcium chloride type 77-80, on Highway 26 and Highway 26 express from the Mont Blanc Tunnel in the Aosta Valley and on Highway 242 to Gardena Valley on the occasion of the 1970 Mondial Ski Championship. These experiments were preceded by a meteorologic study, in which the road was divided into 3 parts corresponding to 3 different altimetrical belts from some hundreds of meters to 1,400 m elevation at the entrance of the Tunnel on the Italian side. The total annual average snowfall forecast was 170 cm. For one experiment, a 15-km section was chosen between the Tunnel and Morgex where, even if the slope is not excessive, cars must have chains or camion tires. The amounts used were of 10 gr/m^2 in the preventive treatments and 40 gr/m^2 in the maintenance treatments. The numerical ratio among these types of treatments was, on the average, 1 to 3. Also described is the Gardena Valley experiment and the modifications made to the equipment.

In the last few years the problem of road safety has assumed a great importance on account of the number of accidents, often fatal, occurring on our roads. Motorization, developing itself much faster than the road network is being adapted and improved, contributes together with the increase in the traffic density to make roads less and less safe.

One aspect of traffic safety, which has not been taken into proper consideration, is the elimination or reduction of accidents due to snow or ice on the road. During the clearing operation, the machines do not perfectly clean the road, and complementary operations are required to remove the residual snow or ice layers. These operations sometimes account for 50 percent of the total cost of the clearing operation. They involve the spreading of salty materials that induce the melting of the packed or frozen snow layers that the snowplows fail to remove. The same materials are efficiently used for removal of glaze and for preventive treatments. The widespread use of the salts, particularly NaCl (sea or rock salt) and $CaCl_2$, has given rise to a series of new problems and questions that require definitions of the effective possibilities, the limit of use, and the working characteristics of the materials used. Above all it is necessary to clarify the true dynamics of the process of elimination of ice or snow treated with salts, which appears as a melting process.

A dry NaCl grain or a dry $CaCl_2$ flake has no direct melting action, and if the air moisture is low, under 40 percent for $CaCl_2$ and at least 70 percent for NaCl, the salt grains remain inert as if they were stone, grit, or sand. The melting only occurs after the salt is dissolved and has formed a solution by taking the moisture from the atmosphere or from the icy layers to be treated. Therefore the efficiency of the grain or flake salts in the preventive applications depends on the vapor content of the atmosphere.

Since the winter of 1965, the use of calcium chloride solutions has been extended, especially on an experimental scale, although the adoption of this technique obviously requires special equipment and the employment of trained specialized labor.

On this point it is necessary to examine the elements that influence the choice between the use of salts and the use of salt solutions. The technique adopted will be influenced by the thickness of the icy layers to be treated and the ambient moisture. The temperature, although it indicates the most convenient type of salt to be used, is not a determinant, especially between certain limits, in the choice of whether the solid or liquid is most advisable.

For thin icy layers, the use of more or less coarse grains may have an influence on the velocity of the melting action, which reaches the highest values when the grains are of a size near that of the layer thickness. For still thinner layers, an excessive grain size will have a negative influence. Generally it may be said that for the removal of a thin layer of snow, small grains are necessary; but for a thicker layer, large grains are required.

Grains smaller than $\frac{1}{32}$ cu in. (0.5 cm^3 corresponding to a sphere with a 2.3-mm radius) have a too rapid superficial dissolution effect and a reduced penetration. To obtain the best result in removing an icy layer requires that the grains completely penetrate to the pavement and be adjusted such that the ice is prevented from sticking to the road. The very small grains penetrate faster but are used up before reaching the pavement. According to Kaufman, the ideal would be represented by a very well-graded mixture with sizes passing and retained by the No. 3 and No. 12 sieves of the Tyler series (from 7 to 2 mm approximately).

In addition to the size of the grain, the penetration is also influenced by the thickness and by the temperature. An explanation of this fact is given by a simple consideration of the grain's specific surface. Suppose we use grains with a spherical form. The ratio of surface to volume is given by

$$\frac{4\pi R^2}{\frac{4}{3}\pi R^3} = \frac{3}{R} = \frac{6}{d}$$

This means that the smaller the grains, the larger the total surface and the greater the possibilities of contact with the icy layer will be.

Regarding moisture, according to a survey made by the Ohio State University, sodium chloride is able to absorb easily atmosphere moisture when the moisture content is very high, higher than 70 percent and generally between 75 and 100 percent, whereas the calcium chloride can absorb moisture when the content is much lower, generally between 40 and 50 percent at a temperature between 0 and -26 C. For moisture values lower than these, the use of both these salts would not be effective.

Eliminating icy layers of the glaze type, i. e., very thin layers of frozen humidity or water, by using anhydrous salts is very difficult for the reasons already given on the relation between thicknesses of the ice and diameter of the salt grains. Therefore the solid treatment has dubious utility. Problems with this treatment include the difficulty of "starting," the salts' solubility under low moisture conditions, and the decrease in the salts' action in relation to the thickness of ice to be treated. In addition there is the frequent breakdown of the spreading machines due to caking of the grains or flakes of salt as well as the waste caused by the salt being scattered by the traffic. In the successive checkings, it is almost impossible to obtain a reliable evaluation of the effectiveness of using the solid material. This doubt has led to repeating superfluous or excessive treatments with increased costs of operation.

For these reasons experiments were carried out during the 1965-1966 winter season by the Azienda Nazionale Autonoma Delle Strade (ANAS) on the use of saline solutions.

The use of the solutions makes it possible to eliminate the disadvantages of the solids, i. e., the difficulty of starting, the solubilizing of the salt under low moisture conditions, and the decrease in the salt action in relation to the thicknesses of ice to be treated. The solutions eliminate the time taken by the salt grains to dissolve and the possibility of failure in starting due to scarce atmospheric moisture; develop a faster action owing to the larger surface of contact between solution and icy layer; ensure an even melting, or at least a road surface evenly prepared because the solution can be spread with fairly good continuity; eliminate the possibility of caking of the grains in the spreading machine, especially when the latter has been loaded in advance and is left waiting; and make it possible to check the residual strength of the solution spread on the road, even after some days.

Having decided to use solutions, we selected calcium chloride instead of sodium chloride for 2 reasons: (a) The eutectic obtained is much "lower" than that obtained with NaCl; and (b) the solubility of $CaCl_2$ in water is facilitated by its exothermic characteristic. When hydrating it gives off considerable heat. On the other hand, NaCl when dissolving absorbs heat from the water and consequently becomes colder and delays the dissolving process.

PROPERTIES OF THE CALCIUM CHLORIDE SOLUTION

Calcium chloride is very soluble in water. Both anhydrous and hydrated (commercial type 77-80 contains approximately 20 percent water), it is hygroscopic, i.e., capable of absorbing the moisture of the atmosphere or of the icy layer by partially or totally dissolving in relation to the ambient vapor pressure and temperature.

The mechanism followed is the same for both the solids and the solutions. These can also absorb the ambient moisture until an equilibrium is established, which is a function of the atmospheric vapor pressure in relation to the temperature. In particular, with the solutions it may occur as both a dilution and a concentration.

This relative instability is obviated by preparing solutions of medium high strength and by checking them later by means of special reagents. In every case, except in very special cases, which will be indicated in the following, the difference in the ambient vapor pressure/solution is not such as to modify substantially the strength of the prepared solution, which varies around mean values corresponding to the forecasts.

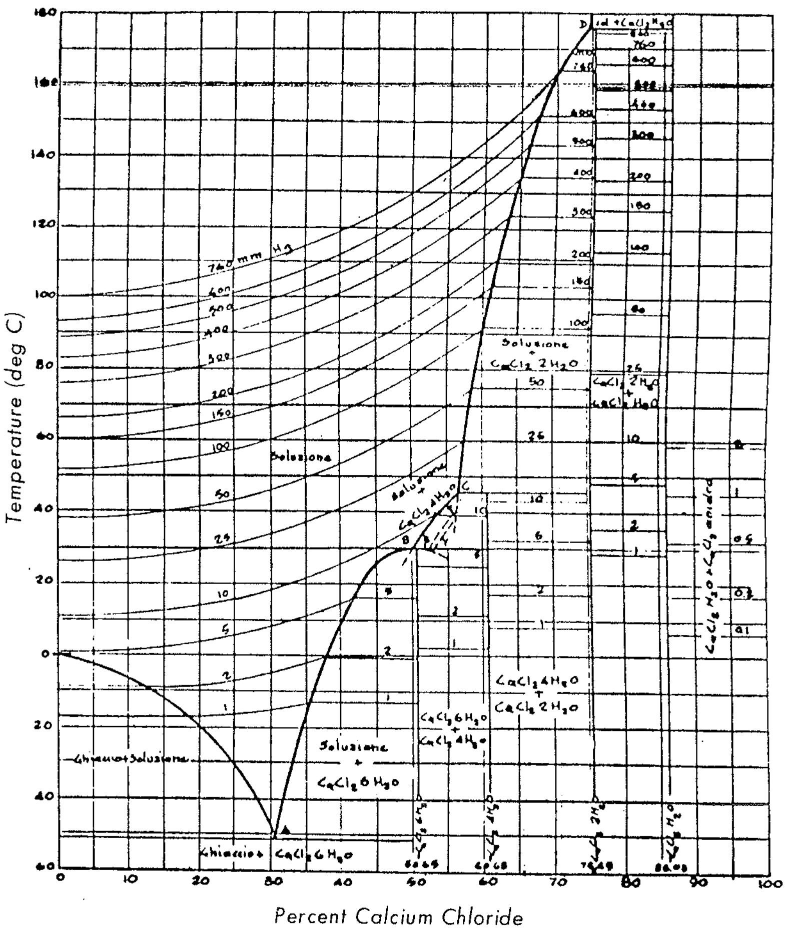

Figure 1. Phase diagram and vapor pressure of the system $CaCl_2$-H_2O.

The solubility data are given in Figure 1. The figure shows the curve of solubility in water of $CaCl_2$ as a function of concentration and temperature. In the upper part above this curve is the area of the unsaturated solutions where the product is thoroughly soluble. Under the curve is the area of coexistence of the saturated solutions equilibrated with ice or solid hydrates as well as mixtures of wholly solid hydrates. Although data for pure $CaCl_2$ are shown in the figure, it is sufficiently valid at least for ordinary uses and also for the use of the commercial product 77-80 in winter.

For preparing the solutions, data shown in this diagram give an indicative value of the concentrations to be used in relation to ambient temperature. It should be kept in mind, however, that this concentration is to be corrected in relation to the prevailing temperature, taking into account the limits of the future use. In other words, to prepare a 20 percent solution with a freezing point of approximately -18 C in an atmosphere at temperature of 0 C, one must "correct" the reading of the densimeter by a certain value by using a table of data determined with a densimeter and a pycnometer set for a temperature of 15.5 C (International Critical Tables).

PREPARATION OF THE SOLUTIONS

Calcium chloride type 77-80 is offered for sale in PVC bags, each containing 50 kg. This salt is a by-product of the industrial production of soda (following the well-known Solvay process) and therefore it is already in a liquid condition. This is helpful if the solutions are used on a large scale.

The choice of the concentration of $CaCl_2$ in the solution depends on the type of treatment, preventive or curative, to be carried out as well as on the ambient atmospheric conditions during the application. According to the experiments carried out, it is advisable to use the following $CaCl_2$ concentrations for the different types of applications: 15 percent for preventive treatments (temperature at which the first ice crystals appear, -10.3 C); and 26 percent for curative treatments (temperature at which the first ice crystals appear, -32.5 C).

Each 250 kg of $CaCl_2$ (5 bags) added to 1,000 liters of water gives approximately 1,100 liters of 15.6 percent solution. Each 500 kg of $CaCl_2$ (10 bags) added to 1,000 liters of water gives 1,200 liters of a 26 percent solution. The 15 percent solution can also be obtained by diluting the 26 percent solution by an equal volume of water.

The solution is prepared as follows:

1. Fill the dissolving container with the amount of water necessary for preparing the solution, the strength of which is given.
2. Pour the chloride in the container, keeping the water agitated by means of a special apparatus. For this operation it is advisable to pour the material gradually in order to prevent the flakes from agglomerating in a mass on the bottom of the tank and dissolving with much difficulty.
3. Keep the whole mass moving to obtain a homogeneous solution without any solid residue.

Because $CaCl_2$ is exothermic, during the phase of the dissolution of chloride in water a considerable amount of heat is evolved, which increases solubility. The order of magnitude of this heat evolution can be appreciated by noting that in the preparation of a 25 percent solution the temperature of water increased by approximately 33 C.

EFFECTIVE USES OF CALCIUM CHLORIDE SOLUTIONS

The calcium chloride solutions may be effectively used in the following cases.

Preventive Applications

The solutions prevent the formation of icy layers (glaze) on the bare pavement due to (a) an ambient temperature of approximately 0 C with a tendency to go down with nebulous formation in the air and humidity close to saturation point (the fall in temperature makes for precipitation of icy particles, which agglomerate and form a continuous frozen surface); and (b) the pavement of the road being wet with rain and the temperature of the surface being about 1 to 2 C above zero. The wind causes the water to evaporate and, consequently, takes the heat from the pavement. Even if the ambient temperature is 1 to 2 C, the water layer freezes promptly. The solutions also prevent the snow from sticking to the pavement.

Maintenance or Curative Applications

By annihilating the cohering action of the snow mass, the solutions fluidify the layers of hard or packed snow, provided they are not completely frozen. The solutions can be applied for eliminating either the snow layers remaining after passing of the snowplows or the fresh snow layers, provided they are of moderate thickness (about 10 cm).

The suggested amounts of 15 and 26 percent solutions are given in Table 1. With these amounts, a 10-m^3 tank can provide preventive treatment of a 220,000-m^2 road surface with 26 percent solution and maintenance treatment of a 100,000-m^2 road surface with 26 percent solution. Therefore, a road with an average width of 5 m can be spread for a distance of 44 and 20 km respectively.

THE MONT BLANC TEST

During the winter of 1965-1966, the department in Turin decided, in agreement with ANAS, to conduct a series of experimental maintenance operations using calcium chloride, commercial grade 77-80, in aqueous solution.

Mont Blanc Tunnel had opened in July 1965 and was expected to have heavy traffic even in winter because of the tourist traffic through Courmayeur and Chamonix. Consequently, it was necessary to study problems connected with winter travel on Highways 26 and 26 express.

At a preliminary stage, the road section to be used in the experiment was delimited by a study of the meteorological features of the district, aiming principally at determining the magnitude and the variability temperature and local humidity as well as the volume of precipitation. In this research, data of the Ministry of Works, the Meteorological Department of the Air Service, the Italian Committee for Glaciology as well as from various special studies were examined. Some of the findings are given in Table 2.

Precipitation was subdivided into the following classes of snowfall for various sections:

Section	Length (km)	Mean (cm)	Maximum (cm)
Tunnel to Pré Saint Didier	11	110	170
Pré Saint Didier to Aosta	32	40	80
Aosta to Quincinetto	58	20	50

This subdivision corresponded to the subdivision in altimetrical zones—0 to 500 m, flat land; 500 to 1,000 m, low mountainous area; and 1,000 to 1,400 m, mountainous zone—which indeed was sufficiently representative of the variability of precipitation and of the number of days of frost according to the altitude level. Based on this subdivision, it has been possible to compare the snow precipitation during the years 1959 and 1960 for the 3 sections. This comparison is given in Table 3.

In consequence of this, it was decided that the experimental section would be between the entrance of the gallery situated after the customs place at the Tunnel and the locality of Morgex, along Highway 26 express in the direction of Aosta (Fig. 2).

TABLE 1

SUGGESTED AMOUNTS OF CALCIUM CHLORIDE

Calcium Chloride	Preventive	Maintenance
Solution		
15 percent, g/m^2	50	210
26 percent, g/m^2	30	120
15 percent, cc/m^2	45	185
15 percent, cc/m^2	25	100
Flake, g/m^2	10	40

TABLE 2

TEMPERATURE AND RELATIVE HUMIDITY IN RESORT OF AOSTA

Month	No. of Days With Temperature Below 0C	Temperature		Percent Relative Humidity	
		Mean	Extreme	7 a.m.	10 p.m.
January	23	-2.4	-12.2	70	62
February	18	-1.7	-12.0	71	55
March	10	+1.4	-12.0	71	50
April	2	+5.3	-4.2	73	45
May	—	+8.7	0	78	49
October	1	+6.3	-3.2	83	57
November	7	+2.0	-8.2	73	60
December	19	-1.1	-9.4	70	64
Total	80				

TABLE 3

NUMBER OF DAYS OF SNOWFALL ON 3 ROAD SECTIONS, 1955-1964

Section	Reference Stations	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964
Tunnel to Pré Saint Didier	Courmayeur	31	23	—	25	26	30	16	35	35	27
	Pré Saint Didier	—	—	—	—	—	—	—	—	—	—
	S. Nicolas	20	17	9	17	12	18	11	—	—	—
Pré Saint Didier to Aosta	Valgrisanche	34	41	28	36	43	47	24	45	43	28
	Rhemes N. Dame	—	—	—	—	—	39	16	44	36	35
	Rhemes S. Georges	42	24	20	29	29	29	16	28	21	25
Aosta to Quincinetto	Aosta	10	7	4	12	—	12	—	6	14	8

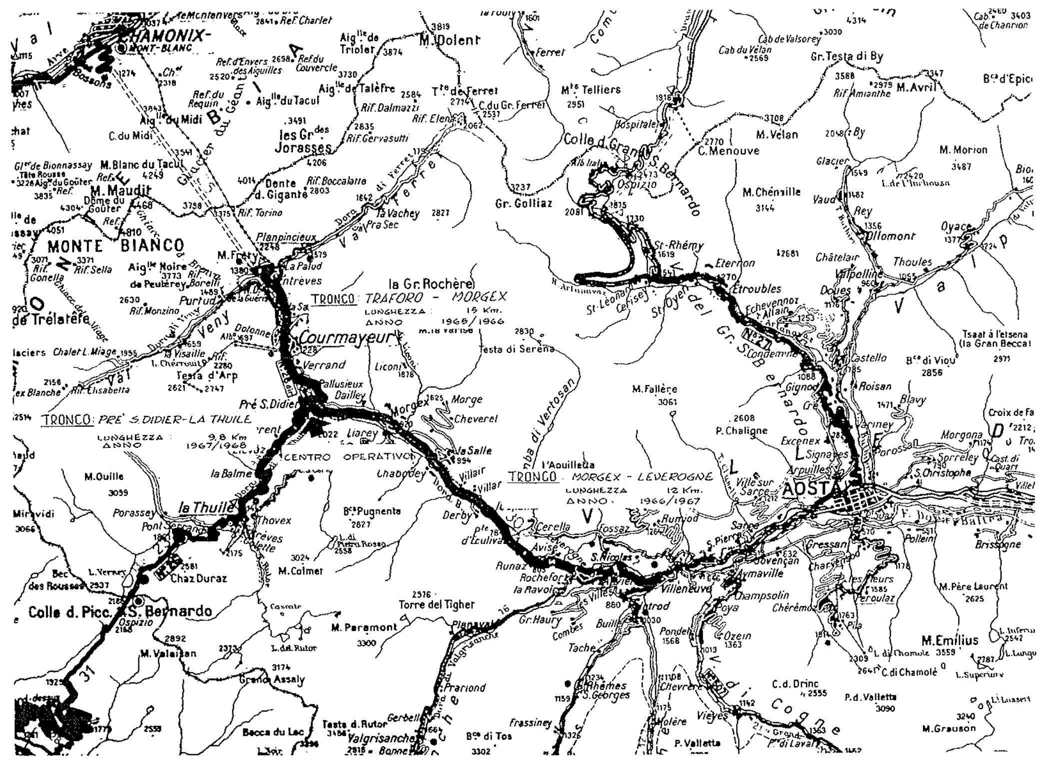

Figure 2. Location of experiment on 3 road sections from the Mont Blanc Tunnel.

In addition to meteorological reasons, this 15-km section was also recommended for other reasons.

From a technical point of view, there had to be the capability to completely treat both lanes at one time with both de-icing (curative) and preventive treatments. In addition there was the matter of moving traffic quickly and safely. It was observed that the altimetrical level features of the road undergo a considerable modification in this section. From 920 m at Morgex, the elevation rises to 1,381 m at the Tunnel entrance, with a mean grade of 3.20 percent. This slope is not exceedingly exacting for the motor freight car trains, which, according to spot checks, begin to put on their snowchains precisely in this section. Because we wanted to keep traffic moving and, consequently, avoid the concentration of the heavy transport vehicles, a considerable percentage of the total traffic, it was deemed useful to facilitate the traffic in this section to a maximum.

For economic reasons and also in view of the experimental nature of the operation, the maintenance operations were contracted to a firm already equipped with suitable machines. The contract work agreement, renewable from month to month, provided that an operating center should be installed in Pré Saint Didier in which the selection container of the chloride was to be set up. Moreover, it was prescribed that the tank should have a capacity of 10,000 to 12,000 kg, be mounted on a truck type 682 (or a similar type), and be fitted with junction pipes to 2 liquid sprinkling bars. These bars were to be made of bronze and fitted with 3 series of interchangeable nozzles in order to regulate the quantity of liquid to be spread on a width of 5.50 m of roadway. The liquid was to be supplied to the bars by means of 2 centrifugal pumps, driven by a 10-hp explosion engine or by the engine of the truck after the required modifications were made. The pressure at the nozzles was to be, in any case, higher than 3 atmospheres. The container was to possess a minimum capacity of 12 m^3 and be fitted with an electric agitator in order to speed up the solution of the calcium chloride in water. The contract did not include the supply of the calcium chloride (provided by the department) or the labor required for the solution preparation operations. It did provide that a specialized driver be permanently present on the working site for the duration of the agreement and be at the disposal of the personnel of ANAS on request, within 30 minutes at most. The monthly charge provided for 60 hours of tanker work, excluding the times for loading, as well as the occasional technical help from the specialized personnel of the supplier firm. Each hour of spreading work beyond the specified 60 hours was to be paid separately according to the provided scale. During the operations, this agreement remained almost unchanged, with the exception of the amount, which was reduced.

The operations included the following:

1. Preventive treatments—A 15 percent solution was prepared in about 20 minutes (temperature of appearance of the first crystals, -10.3 C) and the tanker, after having carried it (average time, 20 minutes), began the treatments in the direction of the Tunnel. The amounts of solution were fixed at 50 g/m^2, corresponding to 10 g/m^2 of solid material.

2. Maintenance treatments—A 26 percent solution was prepared in about 30 minutes (temperature of appearance of the first crystals, -32.5 C). The tanker was loaded in about 20 minutes. The amounts of solution were fixed at 120 g/m^2, corresponding to 40 g/m^2 of solid material.

Owing to necessities, 15 percent solutions were sometimes used for maintenance treatments and 26 percent solutions for preventive treatments. In the first case, the amounts rose to 210 g/m^2, corresponding to 40 g/m^2 for solid material; and, in the second case, they dropped to 30 g/m^2, corresponding to 10 g/m^2 of solid material.

The treatments with $CaCl_2$ solutions began on December 21, 1965; they were continued during the following days either by the preventive procedure or by the maintenance method according to the necessities.

Table 4 gives the data on snowfalls during the winters of 1965-66, 1966-67, and 1967-68. During 1965-66 treatments were limited to the 15-km section between Morgex and the Tunnel. In view of the satisfactory results obtained, the section was

TABLE 4

SNOWFALLS FROM 1956 TO 1968

Date	Number of Days	Depth of Snow (m)
1965-66	43	7.50
Nov. 15-21	6	1.25
Nov. 24-30	7	1.55
Dec. 2-6	5	0.65
Dec. 10	1	0.35
Dec. 21-31	11	1.50
Jan. 2-4	3	0.40
Jan. 11-12	2	0.35
Jan. 21-24	4	0.75
Feb. 17	1	0.20
Feb. 21-22	2	0.20
March 26	1	0.30
1966-67	22	4.50
Nov. 29-30	2	0.65
Dec. 2	1	0.20
Dec. 4	1	0.20
Dec. 12-15	4	0.70
Dec. 23	1	0.20
1966-67		
Dec. 28	1	0.15
Jan. 21-25	5	0.60
Feb. 17-20	4	0.80
Feb. 27	1	0.20
March 18	1	0.20
March 28	1	0.15
1967-66	32	4.95
Oct. 31	1	0.25
Nov. 2-5	4	0.40
Nov. 27	1	0.15
Dec. 26	1	0.15
Jan. 1-2	2	0.35
Jan. 4-14	15	2.05
Jan. 18	1	0.10
Feb. 6-10	5	0.90
Feb. 20	1	0.35
March 21	1	0.25

extended from Morgex to the south in 1966-67, a total of 25 km. In 1967-68 a section was extended from Pré Saint Didier to La Thuile, a total of 35 km (Fig. 1).

ECONOMIC VALUATIONS

During the first winter, frequent inspections were made to obtain operating and cost data.

The cost of salt materials, based on an average utilization of about 250 hr/yr and a mean value of the weight of fresh snow mass of about 100 kg/m^2, is as follows (1):

Materials	Time Work ¢/m^2	Contract Work ¢/m^2
NaCl	0.35	0.40
$CaCl_2$	0.34	0.33
Mixture 1:3 by weight	0.35	0.34

The analysis was made on the basis of the amounts required to melt snow layers about 5 cm thick at a temperature of -5 C. Table 5 gives a summary of the operations during the 3 winters. Average total costs of the contract work amounted to $960/mo. Average costs of the contract work and the material used amounted to 0.15 ¢/m^2. There was a wide range in actual costs, because in preventive treatments the amount of solid material used was 10 g/m^2, whereas in maintenance operations it was as high as 40 g/m^2.

The comparison between the mean costs of operations with solids and with liquids shows an average ratio of about 2 to 1. To appreciate this ratio, one should consider the following:

1. In the analyses of the costs of spreading solid salt materials, labor for loading the tanker was not taken into consideration. Similarly, labor for preparing the solution of the material in the container was not taken into consideration. In a first approach, the 2 items may be considered equivalent; however, according to a more accurate analysis, the economic comparison seems to favor the solutions because of the less amount of time required; 10 m^3 of a 26 percent calcium chloride solution can be prepared and loaded in the tank in about one hour on an average.
2. In the analyses of the costs of spreading solid salt materials, the amounts considered were those required for the complete melting of snow layers 5 cm deep at an

TABLE 5

SUMMARY OF OPERATIONS

Item	1965-66	1966-67	1967-68
Operations	37	42	35
November	—	2	2
December	7	17	7
January	21	16	15
February	9	7	11
March	—	—	—
Hours	89	141	128
November	—	7	5
December	20	69	28
January	48	37	58
February	21	28	37
March	—	—	—
Section length, km	15	25	35
Avg. speed of treatment, km/hr	6.2	6.4	9.6
Avg. width treated, m	6	6	6
Calcium chloride used, kg	80,000	120,000	160,000
Months of actual work	2	3	3
Surface treated per operation, m^2	90,000	150,000	190,000
Avg. amount per operation, g/m^2	24.0	22.2	21.8
Cost of contract work, $	1,920	2,880	2,880
Avg. cost of contract work and material used, ¢/m^2	0.16	0.15	0.13
Ratio of preventive to maintenance operations, percent	40-60	30-70	40-60

outside temperature of -5 C. These amounts were as follows:

Material	g/m^2
NaCl	175
$CaCl_2$	70
Mixture 1:3 by weight	120

These amounts, however, were appreciably higher than those anticipated for the treatments with liquids. Moreover, the specified amounts do not, of course, allow for the effects of the traffic, the time required for the melting, or possible favorable environmental conditions, as for instance the insulation of the sections treated. The currents of air produced by passing vehicles remove a certain part of the solid material, estimated conservatively at 10 percent, from the roadway. In preventive treatments, this phenomenon is intensified because the mass of granules thrown down by the oscillating device of the spreader on 1 m^2 is very small and, consequently, more easily moved by the traffic before it can be charged with humidity and adhere to the pavement.

Other causes include the turbulence of the spreader and the lack of uniformity in the distribution of the salt over the pavement. Moreover, in the operative phases of snow removal, it may happen that the alternation of the successive passes of plows and spreaders is not distributed over the time to make possible the complete action of the de-icing chemical still in the solid state. Therefore, the amount of salts actually utilized and, as a consequence, their efficiency are markedly reduced.

For these reasons, to obtain the same results in preventive treatment by using 10 grams of $CaCl_2$ in solution will require at least 20 gr/m^2 of solid material.

Finally, and especially in the case of preventive applications, the solid-liquid costs ratio seems actually to vary about a value of 2 to 1, whereas, with well-planned curative applications carried out under optimum conditions, this value could be lowered to about 1.5 or 1.2 to 1 as a result of better dispersion and of more complete utilization of the product.

Another important consideration in the cost analysis is that the use of solid material is under time work, whereas the use of solutions is under contract work. In the time work, vehicles are used on an average of about 250 hr/yr, whereas in contract work one has to consider the summer season. Because the major cost is that of labor (over 60 percent), a reduction in depreciation and overhead, which varies with the time of use, is offset by an increase in labor, which remains constant in value. Average costs for both time work and contract work were given earlier.

Operation Checks

During the years in which the tests were made, recrystallization of the chloride on the pavement due to evaporation of the solvent was observed. In order to exclude recrystallization of the salts, which would appear not in anhydrous or pulverulent form (as in the case of sodium chloride) but as a film of dense hydrate in a drying phase and therefore slippery, reagents that tend to ascertain the strength of the solution on the pavement were studied and prepared. It is thought that, because of the accumulation of calcium chloride after repeated treatments, the recrystallization might take place only with less than 45 percent of atmospheric humidity, strong wind, insolation, and a temperature of about 0 C.

Checking of concentration proved thus to be very advisable, especially in relation to the lingering of the solution on the pavement for several days after the treatment. Under conditions of normal humidity (60 percent), the liquid film remained on the pavement for 6 to 8 days and maintained an efficient concentration. It is recalled that for diluting a 26 percent solution to 15 percent requires that it absorb an amount of humidity almost equal to its own volume; and for attaining a strength of 5 percent, the solution has to absorb an amount of water equal to about 4 times its volume in relation to the starting solutions. The strength of the solution on the road is determined by spraying a few drops of a reagent on the pavement. The presence of $CaCl_2$ is confirmed by the formation of a white blur (which is nothing but a salt precipitate) in the sprayed area. If no precipitate is formed, it means that strength is lower than that identifiable with the reagent used.

The following reagents are used:

1. Ammonium oxalate in 3 percent aqueous solution. It gives a white precipitate on the pavement in the presence of a $CaCl_2$ solution between 5 and 30 percent in strength. In view of its high sensitiveness, it is used for determining the presence or the absence of $CaCl_2$ on the road.
2. Sodium sulfate in 5 percent aqueous solution. Positive reaction shows a concentration above 25 to 30 percent.
3. Sodium sulfate in 10 percent solution. Positive reaction identifies a strength above 15 to 20 percent.
4. Sodium sulfate in 25 percent aqueous solution. Positive reaction shows a concentration above 5 to 10 percent.

EXPERIMENT IN THE GARDENA VALLEY

In February 1970, the world skiing championships took place in 3 sport centers of the Gardena Valley. The area is directly accessible by railway. Main direct roads for access are Highway 12 (north-south) from the Brenner pass (Austria-Germany), Highway 49 of the Pusteria Valley (Cortina, San Candido, Austria), and Highway 48 of the Dolomites on the southern versant. Some traffic was expected from the Gardena and Sella passes in the eastern quadrant, but it was restricted by the avalanches and storms, resulting in difficulties for winter maintenance operations to keep these passes opened at all times.

The main drawback along Highway 12 was that which could result from a particularly hard winter. For the Bolzano-Brenner stretch, 1 turbine, 2 snowplows, and 2 spreaders were foreseen as being necessary.

After the tests made on the spot, it was decided that the area most directly requiring efficient operations was the highway of the Gardena Valley. There is no alternative route for traffic here; once traffic enters the road, it is compelled to follow it (Fig. 3).

Organization of Maintenance Operations

Maintenance operations, in which solutions of calcium chloride were used along Highway 242, started from Ponte Gardena, at an elevation of 469 m, and passed through the following localities: Ortisei, 1,234 m elevation and 13.3 km from the starting point; S. Cristina, 1,428 m elevation and 17.3 km from the starting point; Selva, 1,563 m elevation and 20.8 km from the starting point; and Bivio Miramonti, 1,800 m elevation and 26 km from the starting point. Here the roads to the Gardena pass, 2,121 m elevation, and to the Sella pass, 2,244 m elevation, branch.

The low section is between Ponte Gardena and Bivio Miramonti, 26 km, and has the following characteristics: Ponte Gardena to Ortisei—upgrade, medium mountain, and extraurban; Ortisei to Selva—false flat, almost urban, resorts, heavy pedestrian and vehicle traffic; and Selva to Bivio Miramonti—upgrade and high mountain, thinly populated.

These different situations had some influence on the maintenance operations in that on the stretches from Ponte Gardena to Ortisei and from Selva to Bivio Miramonti the traffic is fluid, whereas on the intermediate stretch from Ortisei to Selva the typical characteristics of the winter resort centers prevail with frequent slowing down and some traffic jams. Under normal conditions, this has caused preventive treatments to be carried out during the evening hours when there is a usual pause in traffic and maintenance operations can proceed with a remarkable fluidity.

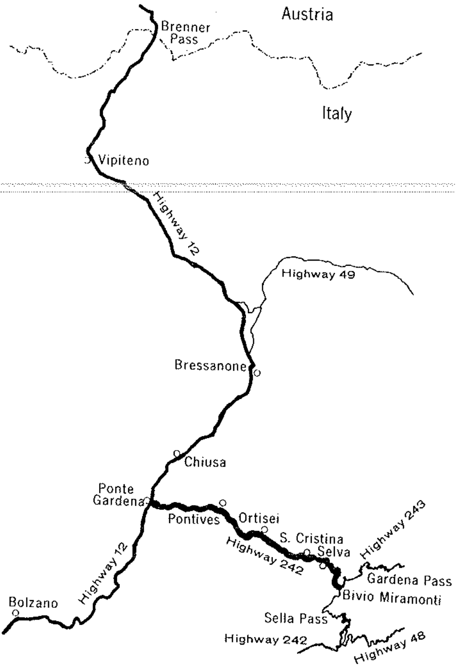

Figure 3. Location of experiment in Gardena Valley.

Equipment

Distributed along Highway 242 were four snowplow blades, two 5-m^3 tankers provided with attachment for a blade, and four rotating devices.

Equipment for Dissolving Chloride

Near the maintenance centers at Pontives and Santa Cristina, 2 containers with a mean capacity of about 12 m^3 were prepared. This permitted 2 loadings per tank per each container prepared. During the period of the championships, it was also decided to prepare the solutions by day, at variable moments, in the containers and to carry out the simultaneous loadings of the tankers alternately from one of the 2 containers. The solution in the empty container was replaced in the period of preventive treatments. At the end of the operation trip, the tankers stopped near the full container, were filled up again, and were placed on the prefixed spots, ready for a possible operation by night. When an operation by night was required, a ready supply container was available in addition to the 2 full tankers.

The 12-m^3 containers were equipped with a screen with a 2- to 3-mm mesh opening for the introduction of calcium chloride and with a pump to make solution recycling easier and to serve initially for water supply. Moreover, with the pump (centrifugal with diesel or electric motor) having a flow rate of about 1,500 liters/min, the tanker could be loaded rapidly.

Tankers

Two 6-m^3 tankers were mounted on a Fiat 639 car equipped with a rear sprinkling bar (sparger) with a flow rate adjustable by means of a centrifugal pump driven by an auxiliary motor. The sprinkling bar was 250 cm in length and 2 in. in diameter. The nozzles mounted on this sprinkling bar made it possible to obtain a flat, broad, and non-atomized jet; this last feature was fundamental.

All the control gears for opening, flow rate regulation, and opening only a part of the nozzles were in the cab. On the 2.50-m long sprinkling bar were mounted 3 pairs of opposed nozzles, K20 and K40, for sprinkling over about 4.50 m. In addition a pair of starting nozzles, P4060 and P40100, were mounted on the left end of the sprinkling bar for watering simultaneously, if need be, the remaining 3 to 3.5 m in the opposite direction of the road. The characteristics of the nozzles are as follows:

	Rate of Flow (liters/min) at Pressure					
Nozzle	0.5	1	2	3	4	Approximate Width Covered (m)
K20	6.5	9	13	16	18	1 to 3
K40	13	18	26	32	36	1 to 3
P4060	10	14	19	23	27	3 to 5
P40100	17	23	32	39	45	3 to 5

Amounts Used

The amounts used were of the standard strength adopted, i.e., 26 percent of calcium chloride (this concentration is obtained by dissolving 500 kg of calcium chloride in 1,000 liters of water). They were as follows:

Application	$CaCl_2$ Solid Flakes (g/m^2)	26 percent $CaCl_2$ Solution (g/m^2)	26 percent $CaCl_2$ Solution (cc/m^2)
Preventive	5	15	12.5
Maintenance	20	60	50

Preventive Treatments

Twelve to 25 cc of 26 percent solution correspond to 5 to 10 g/m^2 of flake $CaCl_2$. The amount necessary for treating the 27 km of Highway 242 in only one direction (about 4 m) is

$$5\ g/m^2 = 12.5\ cc \times 4\ m \times 27\ km = 1{,}350\ liters$$

The flow rates to be distributed by the nozzles were computed from the graph shown in Figure 4. As a function of the various amounts of $CaCl_2$ flakes per square meter and the speed of the tanker, the flow rates in liters/min necessary for the various requirements are plotted as ordinates. For example, at 5 g/m^2 and at a speed of 20 km/hr, a flow rate of 20 liters/min is required when treating a width of 4 m with 3 K20 nozzles opened at a pressure of 0.5 kg/cm^2.

For the various situations requiring preventive treatment, the following are values for sprinkling with 3 K20 nozzles over 4 m in amounts of 5 g/m^2:

Speed (km/hr)	Pressure	Flow Rate (liters/min)
10	0.2	10
20	0.5	20
30	1.0	30

Maintenance Treatments

Fifty cc of a 20 percent $CaCl_2$ solution correspond to 20 to 30 g/m^2 of flake $CaCl_2$. The amount necessary for treating the 27-km Highway 242 in only one direction (about 4 m) is

$$20\ g/m^2 + 50\ cc \times 4 \times 27\ km = 5{,}400\ liters$$

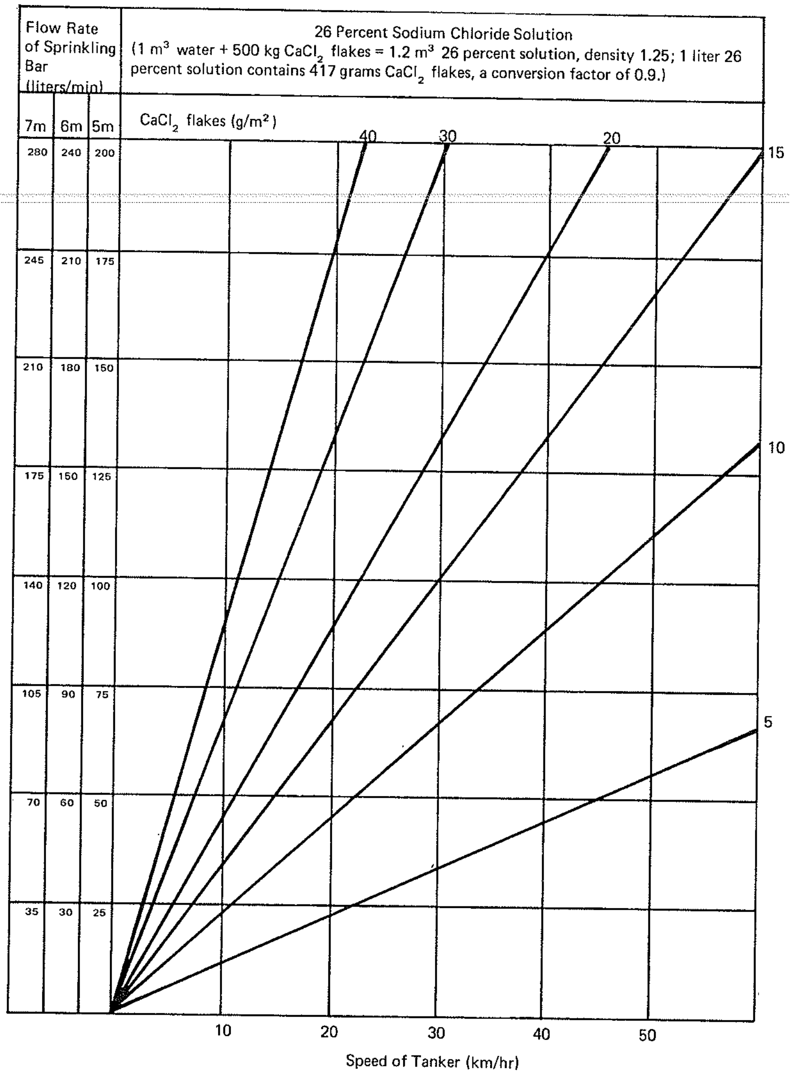

Figure 4. Flow rate of sprinkling bar in relation to speed of tanker and amount of flake $CaCl_2$, type 77-80.

The various flow rates and consequently the relative sprinkling pressure at the bar at the various speeds of the tanker with 3 K40 nozzles open and amounts of 20 g/m^2 are as follows:

Speed (km/hr)	Pressure	Flow Rate (liters/min)
10	0.5	35
20	1.5	70
30	4.0	105

The values with 3 K40 nozzles and 3 K20 nozzles open and 20 g/m^2 are as follows:

Speed (km/hr)	Pressure	Flow Rate (liters/min)
10	0.2	35
20	0.7	70
30	1.7	105

Figure 5. Sacks of $CaCl_2$ and tanker at Pontives.

Operations

From February 1 to 15 there were 7 snowfalls of different volumes. Although preventive treatment was carried out at a reduced amount of 5 g/m^2 $CaCl_2$, the 4 minor snowfalls on February 3-5, 11, 13, and 14 (4, 5, 4, and 8 cm respectively) were controlled without requiring the assistance of the snowplow blades. Only at the end of the snowfall was a control treatment carried out on the amount of 10 g/m^2 of $CaCl_2$ because of the humidity present on the pavement.

Similarly, the other 3 snowfalls on February 5-6, 10, and 14-15, all of 20 cm, were very well controlled, and, with the exception of the first one for which the snowplows started with some delay, the roadway was successfully cleared less than 2 hours after the end of the snowfall. Moreover, during snowfall (except for a few hours of the night from February 5 to 6) the surface of the roadway was not covered with hard snow. On the contrary it was always possible to maintain the snow in a wet and noncohesive state resulting in the use of very little de-icing chemical especially in view of the altitude and temperature.

The photographs in Figures 5 through 13 show the equipment used and the results obtained.

Operating Costs

The analysis of the costs is still in progress. However, the following figures can be given for the entire area (including the Sella and Gardena passes) from November 11, 1969, to February 15, 1970, the period between the first snowfall and the end of the world skiing championships:

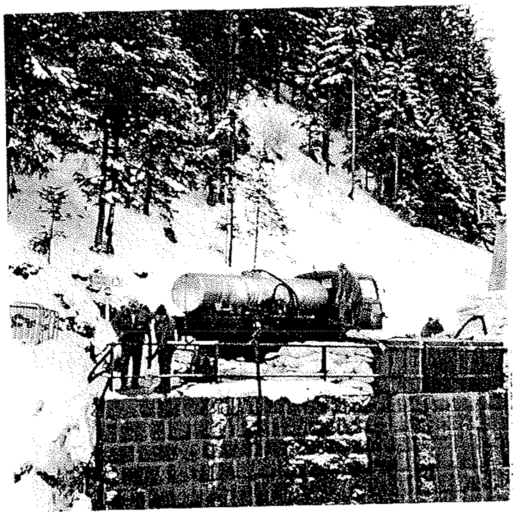

Figure 6. Tanker at S. Cristina.

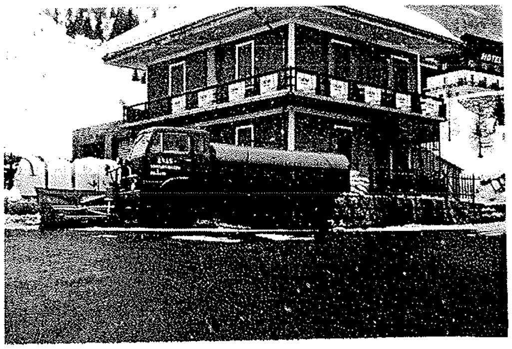

Figure 7. Tanker at Bivio Miramonti going to Gardena and Sella passes.

Figure 8. K40 and P40100 nozzles on sprinkling bar.

Figure 9. Snow after treatment with $CaCl_2$ solution.

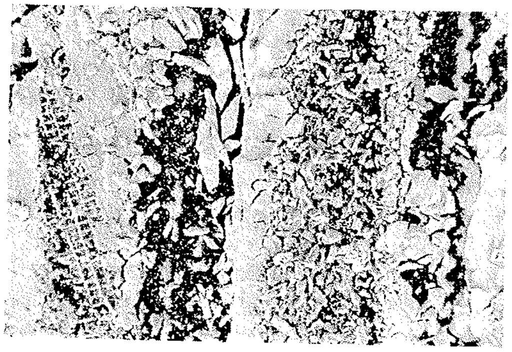

Figure 10. Same snow after solution and traffic have eliminated its cohesion and adhesion to the pavement.

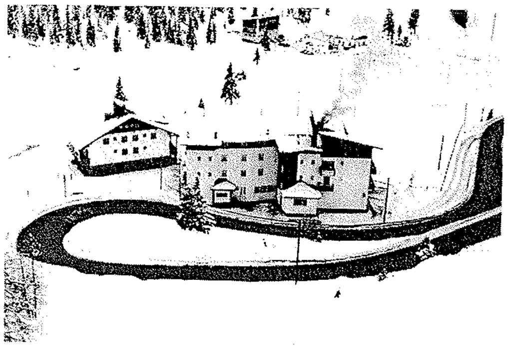

Figure 11. Road at Plan de Gralba after application of $CaCl_2$ solution.

Figure 12. Road at Selva after application of $CaCl_2$ solution.

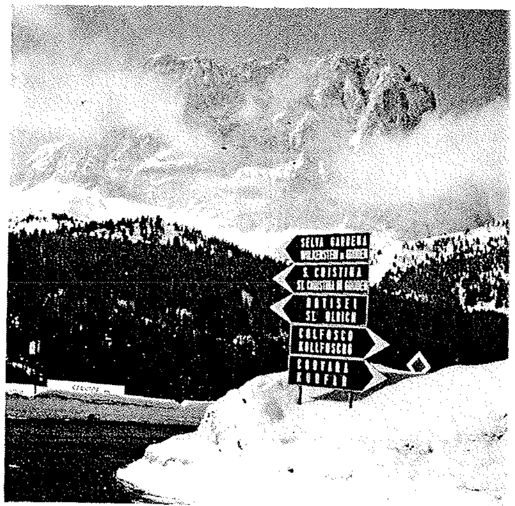

Figure 13. Road at Bivio Miramonti after application of $CaCl_2$ solution.

Number of snowfalls	26
Aggregate depth, cm	165
Calcium chloride used (solid and liquid), tons	267
Number of applications with tankers	77
Average surface treated, m^2	210,000
Time of use of rotating devices, hours	2,100

CONCLUSIONS

The use of calcium chloride in aqueous solution represents a partial evolution of the traditional system of treatment with solid de-icing chemicals. The most significant aspect of this type of operation is that of the preventive treatments.

In addition to eliminating the scattering of the solid material by traffic, this type of treatment results in a higher total efficiency due to a better distribution and a closer contact with the pavement.

The Mont Blanc and the Gardena Valley experiments showed that the preventive treatments performed according to this system are by far more efficient than those carried out with solid de-icing chemical, even when the amount used is lower.

With a pavement "prepared" in this way (beyond the notion that "a salted road does not ice") it has been sufficient as a rule to plow during the snowfall and to apply calcium chloride solutions toward the end of the precipitation to obtain qualitatively high results. Because snow becomes progressively wet and noncohesive, it can be easily detached from the pavement. The final result of the treatments was to eliminate every snow trace and to have a bare pavement.

The solutions may be useful both in preventive and maintenance treatments during or immediately after the precipitation. It seems, however, advisable to specify that, apart from these 2 cases, this application is questionable and of transient effect. Using it to treat thick layers of pure ice or of packed or hardened snow either due to thermal alternations or to the traffic is a mistake, both technically and economically. Under these conditions, the use of solid materials is necessary. Therefore, the solutions should be used timely both in view of the winter season, in order not to operate on "heels" of hard packed snow, and with respect to the separate precipitations.

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Chemical Melting of Ice and Snow on Paved Surfaces

David A. Dunnery

When it is impossible to remove ice from paved surfaces by mechanical means, chemical agents are employed either to completely melt the ice or to partially melt it so that it can be broken up and removed by brooming or scraping. Chlorides, which have long been used for this purpose, are objectionably corrosive. Urea, which is also widely used, is ineffective below the eutectic temperature of 11 F and is marginally effective below ~ 15 F. A noncorrosive liquid agent has been formulated for use at temperatures down to 0 F. During the winter of 1969 and 1970 the agent was tested at LaGuardia Airport in New York and at Union Carbide laboratories. Results of these tests are reported.

Union Carbide first became interested in a chemical de-icer for pavements in response to 2 problems that airport operations crews were encountering in their use of sand. The sand they were using contained varying amounts of water. The freezing of this water in the sand pile created large hard lumps of material that would bind or even break the auger assembly in the sand trucks. Also, when the sand was applied to the runway it was often blown away by the jet blast. It was proposed to treat the sand with an ice-melting chemical that would prevent formation of frozen lumps and, by melting the ice immeidately in contact with the sand, would allow the sand to socket itself in the ice and thus stay put.

This technique was quite successful and is now routinely employed at many airports, among them being those operated by the Port of New York Authority. However, there is strong pressure to avoid the use of sand altogether on runways. Sand is ingested by jet engines where it erodes the turbine blades and can also stick to operational surfaces of the aircraft, such as flap tracks and landing gear. We, therefore, sought to develop a technique of chemical de-icing that would allow complete removal of ice and snow from runways, thus eliminating the need for sand. A proprietary product was developed and submitted for corrosion studies. Any material that comes in contact with aircraft must be noncorrosive to metal and painted surfaces. The material passed the hydrogen embrittlement and cadmium corrosion tests and a sandwich corrosion test in which the fluid is layered between strips of various aluminum alloys and run through temperature humidity cycles. On February 10, 1970, it was accepted by the Air Transport Association for use on runways at LaGuardia.

Meanwhile, we had been testing the product on nonoperational areas at LaGuardia Airport. These tests were of 2 kinds: anti-icing in which the fluid was applied before precipitation, and de-icing in which the capacity of the material to assist in the removal of packed snow and ice was examined.

In our first test on January 6, 2 sections of an asphalt service road were treated, one at 1 gal/1,000 sq ft and one at 1 gal/10,000 sq ft using an agricultural sprayer. A 2-inch snow fell on the area during the night while the temperature was about 24 F. No freezing was observed at the snow pavement interface, and the snow could be completely removed by plowing.

On January 20, a 500- by 30-ft area of a concrete taxiway was heavily treated (1 gal/125 sq ft) to determine the effect of the fluid on braking action. During the night a light blowing snow fell at a temperature of 10 F. The blowing snow stuck to the wet surface of the test area and it was completely snow-covered while the rest of the pavement still had only scattered patches of accumulation. After being plowed, the test area was clean and wet, completely free of snow, while the rest of the taxiway had scattered patches of packed snow.

We did not get an opportunity this winter to test at LaGuardia the protection the agent would afford in a freezing rain. Simulated tests were run in the parking lot at our Tarrytown labs. Test patches were treated with the product at 1 gal/1,000 sq ft. The next morning, at a prevailing temperature of 18 F, water was sprayed on the area as a fine drizzle equivalent to a $^1/_{16}$-in. rain. The water froze immediately on the untreated area, but on the test patch no freezing occurred. Another $^1/_{16}$ in. of drizzle was applied, and again no freezing occurred. Water was then sprayed continuously until crystallization was observed. The ice was mechanically weak and not bonded to the surface. This material was pushed off the treated surface, and the equivalent of another $^1/_{16}$ in. of fine drizzle was applied. This froze to glare ice, but the ice was mechanically weak and not bonded to the pavement, so that it could be readily removed by prodding with a scraper. In these anti-icing tests the agent was applied to the pavement well before precipitation began and, therefore, had the opportunity to work itself well into the surface imperfections. If it had been applied to a wet surface it would have been somewhat less effective, being more susceptible to being swept away in the water runoff.

Our first de-icing test was on January 12 on an asphalt service road at LaGuardia. The surface was plowed after a 2-in. snowfall. Approximately $^1/_{16}$ in. of packed snow remained, with occasional bare spots. The temperature was then 20 F. The road was sprayed with 1 gal/500 sq ft. Melting of the packed snow began immediately and was complete within half an hour.

On February 10, the Air Transport Association approved the use of the fluid on runways. A 1,000-gal agricultural sprayer with a 30-ft spray bar was acquired to permit treatment of larger areas. An extra pump was attached raising its spraying capacity to 120 gal/min. The sprayer was delivered to LaGuardia on February 15 and was immediately put into action.

The storm was then in its twelfth hour, and about 3 in. of snow had accumulated. The temperature was then 21 F. Runway 1331 had been plowed and broomed repeatedly, leaving scattered patches of bare asphalt and packed snow. A 2,000-ft section was sprayed with 1 gal/500 sq ft. Melting of the packed snow began immediately with penetration of the packed snow and melting of the snow-pavement bond. The residual snow could be easily dislodged. Drifting snow eventually covered the test area, but there was no further bonding of snow to pavement.

The snowstorm was followed by freezing rain. At 1:00 p.m., runway 1331 was covered with glare ice between an eighth and a half inch thick. In some places the ice covered partially frozen residual packed snow. A previously untreated area was sprayed with 1 gal/500 sq ft; the temperature was 20 F. Immediate ice melting was noted, attended by snapping, cracking sounds. The de-icer penetrated the ice and destroyed the ice-asphalt bond to such a degree that the ice could readily be dislodged by scuffing the surface. Within 10 to 15 minutes of de-icer application a braking test was performed with a station wagon. The wheels broke through the weakened ice allowing the vehicle to be brought to a controlled stop. Within 15 minutes some areas had melted completely. The residue on the test area was then plowed onto another untreated area and ice melting on the new area was observed.

This proved to be the last storm of the season at LaGuardia, so further opportunities for testing there did not arise. We performed some tests on ice frozen in pans in a cold room at 20 F. The penetration disbonding effect was not observed. Melting occurred only at the ice surface, not at the ice-substrate interface. We prepared test patches in our parking lot by spraying water on asphalt at 18 F. On spraying these with 1 gal/500 sq ft, we again failed to produce this penetrating effect, melting only from the ice surface. We do not know why the kind of action observed at LaGuardia was not reproduced in our lab tests. Perhaps the ice produced in a storm is imperfect compared to that produced in our lab. Perhaps thermal stresses resulting from warming from the 25 F, at which most of the ice at LaGuardia had formed, to the 29 F, prevailing at the time it was treated, had generated microfissures through which the de-icer could penetrate and spread. At present, the possibility remains that glare ice will be encountered on which the fluid is not effective.

The fluid was also tested outside the Union Carbide laboratories in Montreal. There it was applied to areas covered with 3 in. of packed snow and ice representing residual

TABLE 1

MU METER TEST RESULTS

Application Rate (gal/sq ft)	μ	Application Rate (gal/sq ft)	μ
De-icing fluid		De-icing fluid	
0	0.77	1/500	0.67
1/2,000	0.72	1/400	0.65
1/1,000	0.68	Water	0.64-0.65
1/666	0.66		

TABLE 2

MATERIALS COST PER LANE-MILE PER INCH OF SNOWFALL TO PRODUCE INDICATED DEGREE OF MELTING

Temperature (deg F)	15 Percent Wet	30 Percent Wet
30	13	25.8
25	35	71
20	58	116
10	90	180

accumulation from several storms. There were layers of ice interspersed by layers of packed frozen snow. Fluid was applied at a level of 1 gal/125 sq ft. After an hour the material was scraped away. The fluid had penetrated and drained through the packed snow and ice and was now concentrated in the bottom half inch. Over two-thirds of the treated area the material was easily scraped from the surface, the ice pavement bond having been broken.

One further test was run at LaGuardia this winter to determine the effect on braking action of the de-icing fluid applied to a clean dry runway. We wished to learn if the fluid itself was sufficiently slippery to constitute a hazard. This test was run with the cooperation of American Airlines, who provided a Mu Meter, a friction coefficient testing device made by M. L. Aviation, Ltd., and marketed in this country by Soiltest, Inc. The test was performed on the touchdown area of runway 4-22, a concrete runway heavily tire-marked. The fluid was applied to a swath 20 by 500 ft, and the Mu Meter reading was obtained after each application (Table 1). Applications were repeated until the fluid was flowing freely on the surface. A parallel swath was then wet with water and its reading obtained. On the Mu Meter scale readings of 0.6 to 1.0 are rated good. The fluid is, therefore, considered no more deleterious to braking than is water.

Let us now consider how the fluid would be used in highway operations. Its most effective use is as an anti-icing agent applied when an ice storm is imminent. The advantages of a liquid agent are that it can be applied evenly over the surface and it will not blow away as would a solid when applied to a dry pavement. An application rate of 1 gal/1,000 sq ft is sufficient to completely wet the surface if applied in a fine spray. At 10 ft per traffic lane and a fluid cost of 72 cents/gal, this treatment would lead to a materials cost of $37 per traffic lane-mile. The cost may restrict its use to critical areas such as bridges, bridge and tunnel approach ramps, and toll plazas. Here, the fact that the fluid will not lead to chemical attack on metal and concrete structures is an important consideration. The duration of the protection afforded depends on weather and traffic conditions and is thus indeterminate. The user would try to anticipate the icing condition by several hours.

When ice has formed on a highway or plowing has left a residue of packed snow, the fluid may be used as a de-icer. Here, the object is to penetrate the covering, breaking its bond to the pavement and enabling it to be broken up by traffic or removed by subsequent plowing. For ice up to an eighth of an inch or packed snow up to half an inch thick, an application rate of 1 gal/1,000 sq ft should be sufficient. The rate of action depends somewhat on temperature. At temperatures above 20 F action should be complete within half an hour even in the absence of agitation from passing traffic.

Another possible use of the fluid is in direct application to fresh snow in order to keep the snow plastic and mobile. Schaerer reports that snow containing 15 percent free water resists compacting and snow containing 30 percent free water was removed by traffic. The amount of agent needed to produce this degree of melting is a function of temperature. Knowing the water content that the agent would achieve on coming to equilibrium with ice at any given temperature, one can calculate the ice-melting capacity of the agent at that temperature. This calculation has been performed for 4 temperatures, and the results are given in Table 2 as materials cost per traffic lane-mile per inch of snowfall. The slush produced by this technique would differ in one important respect from slush produced by thermal melting. It would not freeze solid on subsequent cooling. Ice would freeze out as the temperature dropped, but some liquid would remain even to temperatures below zero keeping the slush plastic and weak.

Informal Discussion

John A. Cook

What fluid are you putting down?

Dunnery

The fluid is Union Carbide UCAR runway de-icing agent. It is a proprietary product, and I am not free to disclose its composition.

Don L. Spellman

Was the snapping and cracking you observed caused by the salt working its way underneath?

Dunnery

Yes, the ice was buckling and breaking as the material was spread.

Spellman

Pulling the ice away?

Dunnery

Yes, we could see the evidence.

J. G. Slubicki

If this fluid is used as an anti-icing agent, is it effective for a couple of hours or a couple of days?

Dunnery

This has not yet been determined. It would depend to some degree on how actively it is removed by traffic. I would expect the amount of protection to decline with time, but the rate would depend on traffic, weather, wind, and so forth. We do not know how long its effectiveness will last.

J. W. Renehan

How does this compare with liquid calcium?

Dunnery

In what respect?

Renehan

With respect to cost and efficiency.

Dunnery

I have not made any direct comparison. The cost of this fluid is 72 cents per gallon. I do not know what you would pay for calcium chloride.

Renehan

Calcium chloride in solution will do the same thing. I do not know what the range of temperature is for your solution, but calcium chloride in an aqueous solution will work at -10 F. I imagine it will also hold as good, but it is corrosive.

Dunnery

That is right. Calcium chloride cannot be considered for use on runways.

William F. Limpert

What is the vapor pressure of the material?

Dunnery

I do not know.

Limpert

This will have an effect on how long it is going to last.

Dunnery

It is a multicomponent system, and its vapor pressure will change with time; that is, as the more volatile materials disappear, the vapor pressure decreases. I do not know what the initial vapor pressure is; at 25 deg, the initial vapor pressure would be about 5 mm.

Limpert

Is it soluble or miscible in water?

Dunnery

Yes. No material would be effective as an anti-icing agent if it did not dissolve in water.

Limpert

My point is that, if it does have a very low vapor pressure and does stay around longer than salt brine or calcium chloride brine, this alone can contribute to corrosion merely by keeping metal moist even though by itself the material may be noncorrosive.

Dunnery

It would actually protect moist metal.

Limpert

Does it act as an inhibitor against moisture?

Dunnery

Yes. There is one more point I would like to make with regard to the environment. Ninety-eight percent of this formulation is bio-degradable immediately upon being exposed to the environment, so it would not be persistent in the environment.

Snow and Ice Control in California

Carl E. Forbes, Carl F. Stewart, and Don L. Spellman

This paper describes the present operations for snow removal and ice control in California where problems result from a variety of factors such as complex weather conditions, vast differences in elevation, wide temperature ranges, and changing traffic patterns. The paper includes a discussion of a research project initiated to study bridge deck heating and motorist and maintenance warning systems to minimize the hazards of frosting. Also discussed is a study to find a de-icing chemical for use as an alternative to the chloride salts. A comparative test was established to measure the rate as well as the quantity of ice that could be melted at various temperatures. Also considered was the effect of the chemicals on the friction factor of concrete; the corrosivity to steel, concrete, and other materials; the environment, including streams, domestic water supplies, fish, and plant and animal life; and maintenance personnel who will distribute the chemicals on the roadway.

California lies between the thirty-second and forty-second parallels of latitude. Elevations range from more than 200 ft below sea level in Death Valley to over 14,000 ft above sea level in the Sierra Nevada and Cascade mountain ranges. Approximately one-fifth of the state lies above the 5,000-ft elevation level.

This combination of range in latitude and range in elevation results in a multitude of different snow conditions. Although 5,000 ft is generally considered as the normal snow line, occasional heavy storms will fall as low as 500 to 1,000 ft above sea level. Although this is particularly true in the northern part of the state, it is not uncommon in the high desert region.

PRESENT OPERATIONS

Snow removal operations are performed on some 4,600 miles of the state highway system. Snowfalls range from a trace to over 750 in. annually at locations such as Donner Summit on Interstate 80.

Because of the extent and variation of the snow removal operations in California, it is almost impossible to concentrate equipment and extremely difficult to shift equipment from one location to another. Snow is removed from the Laguna Mountains east of San Diego and just north of the Mexican border all the way to the Oregon border. Storms in the southern part of the state will generally deposit snow in fairly concentrated areas and generally above the 5,000-ft level.

The mountain ranges lying to the north and east of the Los Angeles basin are heavily used for recreational purposes and have many miles of highway above 7,000 ft. Along the Sierra Nevada range toward the north, the snow line steadily decreases with the increase in latitude. On many occasions, heavy snowfall will occur in the entire northeastern corner of the state.

Temperatures during the winter have been measured well below -40 deg, and high winds frequently cause blizzard conditions on trans-Sierra routes and on US-395 just east of the summit of the Sierra Nevada mountain range. As a general rule, the snows on the west slope of the Sierra Nevada range are very wet while those on the east slope are extremely dry.

Guides to crews working in this operation define the level or quality of maintenance as expected in snow removal as follows:

Snow Removal

Snow should be removed from state highways as it falls, except on roads having extremely light winter traffic, which are closed after the first heavy snow.

Snow should be removed to the pavement surface for the full width of the traveled way. Widening to provide storage space for the next snowfall should immediately follow traveled way snow removal.

Areas within the right of way in front of stores, resorts, service stations and other roadside business establishments which serve the general public should be kept clear of snow when such areas have been graded and paved by the owner of the abutting property, so that heavy equipment can be operated.

Areas within the right of way adjacent to the traveled way which have been established to provide for public parking, such as locations where the public has access to snow sports, should be cleared. Snow should be removed from established public parking areas after the highway is cleared and equipment becomes available.

State forces will not remove snow from approaches leading from the traveled way to private property, but will operate so as to cause the least inconvenience to property owners. The windrow placed in front of approaches should be removed.

State forces are to assist local authorities in opening public road connections.

Chains shall be required when, in the judgment of the maintenance supervisor on duty, the road surface becomes unsafe for vehicular traffic due to snow and ice conditions.

Ice Control

Where ice, frost or snowpack causes slippery pavement, abrasives and/or chemicals should be applied. The treatment to be used shall be determined by the immediate supervisor in charge of maintenance of the particular section of highway. In areas subject to heavy snowfall, prolonged freezing temperatures and heavy traffic abrasives and/or chemicals should be spread on the pavement at the beginning of a snowstorm to prevent a snowpack from forming and to facilitate snow removal.

Patrol

On routes where freezing conditions are anticipated, special patrols should be scheduled on a continuous basis for the detection and correction of slippery conditions.

Bridges, Shaded Areas, and Other Known Isolated Locations of Acute Icing Conditions

Abrasives and/or chemicals should be applied at the beginning of a storm or whenever icing appears imminent.

Bridges which have a tendency to ice, especially when the approaches may be dry, should be given high priority attention both in patrolling and ice and frost prevention.

Under average winter conditions, sufficient plowing equipment is assigned to all snow stations to handle the amount of snow normally expected. Much of this equipment is geared to year-round use. This includes motor graders, dump trucks, and front-end loaders.

On lightly traveled roads at lower elevations, snow equipment generally consists of 2-ton or 4-ton dump trucks and a motor grader. With the addition of medium-sized reversible snow plows, the trucks used during summer weather are sufficient to remove the light snow or slush. During cold weather, a tailgate-type hydraulically operated chip spreader can be added for sanding and salting icy or frosty spots on the roadway. This combination can handle up to 10 or 15 miles of low elevation snowfall without much trouble providing the average daily traffic on the route is light.

On the main trans-Sierra artery, I-80, between San Francisco and Salt Lake City, we have constructed 3 major snow removal stations to house snow equipment and personnel to ensure that bare pavement will exist as often as is humanly possible during any 24-hour period. At these stations, both multipurpose and highly specialized snow removal equipment is assigned for winter work.

We now operate 73 rotary snowplows of various makes and ages. Our practice is to assign the newer rotaries to those areas having the trunk line through routes north to

Oregon and east to Nevada and the older rotaries to routes having low traffic density and winter closure points (by policy) somewhere short of the summits.

There are 528 displacement plows fitted to a variety of trucks of from 2- to 8-ton capacity. In addition, there are 140 four-wheel drive motor graders available for snowplow work. These graders are equipped with large hydraulic reversible push plows along with grader blades used for removal of packed snow and ice.

Various combinations of sand, cinders, and salt are used for icy pavement control depending on the location of the highway and bridge decks being treated. This material is spread with spinner-type chip spreaders, some of which are mounted under the tailgate of the dump trucks and some of which are bunker-type of 5-ton capacity permanently mounted for the winter onto the truck chassis. During 1968-69, 22,000 tons of rock salt was purchased for snowpack and ice removal throughout the state. Some 270,000 tons of abrasives such as sand or cinders were either purchased or made and then distributed and stored. Two districts, one in the northern end of the state and one on the eastern side of the Sierra Nevada Mountains, operate their own plants during summer months for producing screenings for winter use. Material is obtained from natural lava pits where the supply is practically unlimited and where the purchase of sand for this purpose is not economically practical.

Since the advent of raised pavement markers, the Department is currently experimenting with rubber snowplow blades for snow removal in the lower elevations. Raised markers are being used up to approximately the 2,500-ft level. From data that will be collected this winter, a better indication of the value of rubber blades will be obtained.

Snow removal in the higher elevations in southern California is also conducted on a 24-hour basis to ensure movement of the largest concentration of vehicles in the nation. With the exceptions of Cajon Pass Route (I-15) and Ridge Route (I-5), nearly all other routes subject to snowfall lead to or are in recreation areas.

Because of the snow sports available in the mountain areas of the south and the thousands of persons wishing to take advantage of the numerous, close-in winter recreation areas, one of the major problems is traffic control. In this respect, the California Highway Patrol works in close cooperation with the Division of Highways.

Facilities for the maintenance of all-year routes with bare pavements are necessarily large and complex. One example is the Kingvale Station constructed in 1961. It now consists of a 3-story dormitory that includes a large kitchen-dining room, recreation room, and individual bedrooms to house approximately 70 employees. Other facilities include a 32-bay truck shed with foreman's office, mechanics shop, and radio communications equipment room; a carport for private cars; a storage building; and a sandhouse with a separate gravity feed bunker for salt storage.

During summer months, the station is staffed with a foreman, an assistant, and 6 maintenance men. In the winter, limited-term personnel are recruited and supplemented by men from the valley crews as needed. The winter crew at this station consists of between 40 and 70 men depending on the intensity and duration of a storm. This station maintains 22 centerline miles of 4-lane divided freeway above the 6,500-ft elevation level. In addition to the routine maintenance equipment at this station, there are approximately 30 pieces of heavy snow removal equipment including 9 four-wheel drive motor graders, 6 modern rotary snowplows, and 8 trucks varying in size from 2 to 6 tons equipped with displacement plows.

One problem, which is increasing with the growth of recreational resort areas, is the necessity to dispose of snow by means other than those of plowing or blowing. Growth such as that found in the Lake Tahoe area and in the southern California resort areas requires that snow be hauled to designated disposal sites. Rotary plows equipped with directional chutes are used for loading. Trucks for hauling are the conventional 3-axle, 10-cu yd type. At the dump sites 1 or 2 tractor dozers are employed to stockpile snow and keep the disposal site in traversable condition.

Of the 9 trans-Sierra routes, 4 are closed with the first heavy snowfall of winter. Closures for the most part are in the 7,000-ft elevation range. Most of these routes are closed from November through May. At the end of winter, tractor dozers and rotary plows are used to remove the snow from the routes that have been closed during the snow season. Steady improvements in the capacity of snow removal equipment, particularly rotary plows, have reduced the time to open these passes to an average of 3 weeks and the number of shifts a day from one to three.

Avalanche control is necessary on US-50 during winter months. Overhanging cornices build up several hundreds of feet above the highway, and artillery fire and explosive shells are used to trigger avalanches at preselected times when the road is temporarily closed. Two locations on this route have permanent platform gun mounts for a 75-mm recoilless rifle. The remaining 2 locations can be reached with a portable compressed-air gun. To date, we have been successful in preventing any serious accidental avalanche problem.

The Equipment Department works in close cooperation with field maintenance forces on the upgrading and improvement of all equipment used for maintenance of highways. As an example, when I-80 was completed over the Sierras, it was apparent that greater efficiency in the use of rotary snowplows would be necessary in order to keep the cost of snow removal work within reasonable limits and at the same time retain the high standard of traffic service to which the public had been accustomed. One of our older Snogos was rebuilt and equipped with a diesel engine for powering the augers and blower system. Later improvements to the cutter augers were made. A Rolba ribbon-type cutter was substituted for the original conventional 3-auger system. When measured in tons per hour of snow removed, the modified Snogo was 93 percent more efficient. Since this first unit was placed in operation, a total of 20 older Snogos have been rebuilt. To eliminate continued replacement of bottoms in bunker-type sand trucks, which rust through rapidly from salt, the Equipment Department is now furnishing stainless steel bunkers.

Specialized units that have proved to be labor saving in snow removal and ice control work are Hydro sanders, which replaced the old Missouri-type traction-driven sanders; air-operated snow post drivers with a magnetic holder built into the post leads; and B-type hydraulic reversible plows with a standardized frame and hoist assembly that is readily adaptable to several different truck sizes. This plow, working in 4 in. of snow, will displace approximately 2,290 tons of snow per hour when traveling at a speed of 25 mph. We are experimenting with a hydraulically operated vibratory grader moldboard mounted on a 4-wheel drive grader for use in removing ice pack from the pavement.

Most of the snow removal equipment is radio equipped. Base stations are maintained at each of the 85 highway superintendents' offices in the 11 district offices as well as at headquarters in Sacramento. Basically, operators of snow removal equipment can communicate directly with each other, with the foreman's mobile unit, and with the superintendent's office.

Road and weather information during winter months is reported on a daily basis. This information is accumulated in the territory superintendent's office and relayed to a district office. Here it is again accumulated and relayed via tape or teletype to the Sacramento headquarters. During all storms in winter months, headquarters communications operates on a 7-day, 24-hour basis. During these periods, information is disseminated to 14 broadcast stations hourly, which in turn transmit road conditions to the public. In addition, the Division maintains automatic telephone answering equipment located in several areas throughout the state. Information for this service is updated continuously.

In the 4 districts where most of the snow removal work occurs, foremen and superintendents' cars and pickups are equipped with a California Highway Patrol radio. The Patrol is also equipped with the Division's channel. The Division also maintains direct teletype communications with the states of Nevada, Oregon, and Washington for the exchange of road and weather reports.

VALLEY BRIDGE DECK ICING

In California's central valley area, where the temperature seldom falls below 20 F, flash frost or ice forms on bridge decks but not on the approach roadway. This spot icing is hazardous to motorists, and records show a sharp increase in accidents in the last few years due to this phenomenon.

The present motorist warning system of impending icing danger is a standard metal sign with the message SLIPPERY WHEN WET OR FROSTY. This is ineffective, primarily because the sign is continuously visible to motorists, even in the summertime, and as such becomes an accustomed standard fixture along the roadway.

Because icing is intermittent and cannot be forecast, regular sanding patrols are not maintained. The icy bridge deck problem in the valley area is usually handled by one of the following procedures:

1. When there is a high potential for deck icing, a crew will stand by to apply a salt-sand mixture if necessary;
2. The Highway Patrol informs local maintenance personnel after ice has formed; and
3. An ice-preventive saline solution is periodically sprayed onto the decks. Each application is effective for approximately 3 days.

Adverse ramifications of these procedures are as follows:

1. Bridge deck salt-sanding is an additional task to valley maintenance personnel and results in extensive overtime work;
2. Bridge deck salt-sanding in a valley environment is usually done under the hazardous conditions of darkness, foggy weather, and high-speed traffic (the latter is usually more of a hazard to valley sanding crews than to mountain crews because of the valley motorist's unawareness of an icing problem);
3. When the Highway Patrol reports icing, it usually means the deck will have been iced for considerable time before maintenance personnel arrive to salt-sand;
4. The saline solution preventive method accelerates deck deterioration; and
5. Regardless of the application method, de-icing salts are causing deterioration in decks that have heretofore been maintenance-free.

Basically, the valley bridge deck icing problem falls into 2 areas: (a) safety to motorist and to maintenance crew, and (b) premature deterioration from de-icing chemicals.

Research

With an objective of alleviating these 2 problem areas, a research project was initiated in 1968 that consisted of (a) enclosing the underside of 6 T-girder spans to form simulated box-girder spans; (b) providing heat in three of them; (c) providing a motorist warning sign that is readable only when illuminated; and (d) installing telephone relay systems to local maintenance personnel. The sign and telephone relay systems are activated by ice detecting mechanisms.

Enclosures—Two spans of each of 3 structures were enclosed by attaching 1-in. thick urethane foam sheets to the bottom of the girders. Mastic between all joining sections made the enclosure airtight. Electrical resistance cables provided heat in 1 of the 2 spans so enclosed on each structure. The purpose of a nonheated span was to determine the effectiveness of dead air space under the deck in preventing frost from forming on its surface. Heat in the heated span was controlled by a thermostat and was on when the outside temperature was below 38 F. The amount of heat furnished could be manually controlled from 2½ to 10 W/sq ft of deck area. Thermocouples were placed in the surface and soffit of the deck in the enclosed spans and an adjacent nonaltered span, in the open space of the enclosed cells, and in the air alongside the bridge. Honeywell 20-point recorders continuously recorded the temperatures on a 5-minute cycle from midnight to 10:00 a.m. each day during the 3 months of potential frosting, December, January, and February.

Ice Detectors—Ice detectors manufactured by 3 different companies were installed: Nelson, Econolite, and Holley. Sensing transducers of the detectors were placed at the deck surface in the center of the inside traffic lane. The detectors were connected to the motorist warning sign and to maintenance telephone relay systems. The Honeywell recorders monitored the detectors.

Motorist Warning—An extinguishable message sign was installed on an approach 600 ft from one of the bridges. The 8-inch high letters of the message ICY BRIDGE are illuminated from behind by flashing flourescent tubes. When the tubes are not lit, the letters blend in with the blank face of the sign, thus making the message indiscernible. Motorists' reaction to the sign was documented by a 2-man team, one at the sign and one at the bridge. They recorded any evidence of reaction such as brake lights coming on or sound of engine deceleration.

Maintenance Warning—Ice detecting mechanisms were connected through a telephone relay to a bell and flashing light in a highway patrol office in one area and in a continuously manned bridge tender's office in another. Local highway maintenance personnel were notified when a system was activated.

Results

For several reasons, such as shipment delays, priorities, high water, and failures, the entire installation was not completed until January 1970. Most of the system, however, was operating during the 1968-69 winter. Not too much was learned during this first winter, though, because it was very mild with respect to frosting or icing conditions. The air temperature dropped below 30 F only twice during the winter; the minimum was 26 F. Consequently, very little pertinent data are available from the 1968-69 winter. Data are being collected during the 1969-70 winter, but have not been analyzed in time to be included in this report.

There was a sufficient number of days during the 1968-69 winter with the minimum temperature in the low 30's, low enough for frosting to occur, to determine that the deck surface temperature over the enclosed but unheated spans followed very closely the deck surface temperature over the open span. In other words, the entrapped dead air space of the enclosed span had little effect on the deck surface temperature. There was about an 8 F temperature differential between the surfaces over the heated and open spans when 10 W/sq ft of deck area was applied to the heated cells.

During 3 occasions when heavy frost was forecast, the observation team observed motorists' reaction to the warning sign. On each occasion the temperature was low enough for frosting, and frost did form on the rails, but none formed on the deck. Because there was evidence of frost, the sign was turned on manually to observe motorists' reaction to it. On one occasion the reaction was very poor. Of 105 cars only 24 percent reacted; of 60 trucks, 23 percent reacted. On the other 2 occasions the reaction was better, but still not outstanding: reaction by 44 and 56 percent of automobiles and by 29 and 66 percent of trucks. Buses were included as trucks during the observations. Of 3 school buses that approached during one observation, only one driver made a discernible reaction: He applied his brakes after he was on the bridge.

The very mild winter prevented a thorough check of the ice detecting equipment. Based on this limited experience, however, the frost detectors are apparently not effective on bridge decks in the California valley area. The problem is in the moisture-detecting sensor. It appears that it is possible for enough moisture to be present to cause deck frosting, but not enough to act as a conductor between the electrodes of the moisture detector. Logically moisture would evaporate more rapidly from the heating element than it would from the deck at low temperature. When there is an abundance of moisture, this difference in evaporation rate would not be a problem; but it is when there is a minimum of moisture. Bridge deck frosting usually occurs with little moisture. Unsuccessful attempts were made to correct this problem by lowering the temperature of the heating element. More work along these lines was planned for the 1969-70 winter.

CONCLUSIONS

Based on the data collected thus far, the following conclusions seem warranted. These conclusions may be modified when all data are analyzed or when colder temperatures are experienced.

1. Dead air space under a deck, as occurs naturally in a box girder type structure, has little effect on deck surface temperature.
2. On the average, less than 50 percent of the motorists react adequately to an illuminated warning sign with the message ICY BRIDGE.

3. Conditions that lead to frosting on bridge decks in the California valley area appear to lie within ranges that are too sensitive for the ice detecting mechanisms currently available.

DE-ICING CHEMICALS

Because of the increasing use of chloride type de-icing salts, corrosion of bridge deck steel has resulted in a substantial amount of spalling of the concrete and subsequent repairs (1, 2, 3, 4, 5). As a result of the bridge deck reinforcing steel corrosion, some extensive studies have been made of de-icing chemicals other than chlorides (6, 7, 8, 9). Factors considered were (a) effectiveness and cost of melting ice, frost, and snow; (b) effectiveness and cost of preventing ice and frost; (c) corrosivity of the chemical to metals; and (d) effect of the chemical on the durability of construction materials, such as concrete and bituminous products.

A total of 17 different candidate chemical de-icing agents were subjected to various laboratory and field tests. Although all agents were not subjected to the same array of tests, those chemicals tested were as follows: sodium chloride, calcium chloride, sodium formate, tripotassium phosphate, tetra-potassium pyrophosphate, formamide, urea, sodium acetate, sodium benzoate, calcium formate, magnesium sulfate, trisodium phosphate, potassium oxide, sodium silicate, sodium sulfate, sodium pyrophosphate, and sodium hexametaphosphate.

Laboratory Ice-Melting Tests

The results of the laboratory ice-melting tests show that the melting rate of ice by various chemicals can be mathematically described. Also, the slope of the line in the regression analysis is apparently an "efficiency" term that can be used to compare various chemicals. However, the actual melting of ice is only applicable to a laboratory comparison and not necessarily representative of field performance.

Laboratory Ice Prevention Tests

Concrete slabs were cast and wet with solutions of various chemicals to determine the parameters of ice and frost prevention. The slabs were cooled to 0 F, placed in a room with 85 to 95 percent relative humidity, and observed for the formation of ice and frost. Other than sodium chloride, tetra-potassium pyrophosphate (TKPP) was one of the better ice prevention chemicals tested in this manner.

Field Skid Testing

Limited skid tests were performed by comparing solutions of sodium chloride and TKPP on an average-textured concrete pavement. A 60 percent concentration of TKPP temporarily reduced the friction factor of the concrete pavement. However, with a standard spread of sand being applied to the solution on the pavement surface, there was a significant recovery of skid resistance. Even without sand, the skid resistance, in all cases, recovered with time as a result of the evaporation and absorption of the water. A 30 percent solution of TKPP with and without the sand application has about the same effect on skid resistance as a 30 percent solution of sodium chloride.

Effect of the Chemicals on Air-Entrained Concrete

The effect of tap water and saturated solutions of sodium chloride and sodium formate on concrete was investigated. Sets of concrete cylinders containing 4½ and 7 sacks of cement per cubic yard were alternately immersed in each solution, then oven-dried at 140 F. Sodium formate caused rapid disintegration of the concrete. Visual observation and concrete length measurements indicate that sodium chloride slowly caused disintegration, while as expected, tap water had no measurable effect. Similar testing has been initiated using a saturated solution of TKPP, and thus far, the only conclusion that can be made is that TKPP does not attack concrete as rapidly as sodium formate.

Effects of the Chemicals on Steel

All de-icing chemicals tested that were dissolved in distilled water were corrosive to steel. Depending on the concentration, urea was more corrosive to steel than sodium chloride. To simulate concrete, we added lime to the corrosion test solutions. Sodium chloride was the most corrosive followed by urea and sodium formate. The least corrosive to steel was TKPP. However, the lime water containing all chemicals should be corrosive to zinc and aluminum because of the high pH. Because of the possibility of the nitrogen-type of de-icers penetrating into cracks that are usually filled with soil or sand, these chemicals may be converted into highly corrosive nitrates by bacterial action.

Ecology and Toxicity

Numerous chemicals were investigated for toxicity and their possible effect on the ecology. From a toxicity standpoint, TKPP should be handled in the same manner as sodium and calcium chloride. From an ecology standpoint, nitrogen compounds, or those chemicals that can degrade into nitrogen compounds, are the ones most likely to "burn" plants and stimulate algae growth in adjacent streams. In addition, the nitrogen compounds, as nitrates in ground waters, are being currently studied by others for their toxic effects on infants (14). Phosphate compounds appear to be less potentially active in their effect on the environment than are nitrogen compounds.

Laboratory Ice-Melting Tests

In California, de-icing chemicals are used in the following ways: (a) They are spread on the pavement or bridge deck to prevent the formation of ice and frost; (b) at the beginning of a snow storm, they are spread on the surface to partially melt the snow and also to break the adhesion of the snow to the pavement surface; and (c) during and after a snow storm, the crystalline chemicals are spread on the surface to melt and break up the structural properties of the compacted snow.

Two methods for the application of the chemicals have been used: (a) The salt is dissolved in water and the solution is sprayed on the pavement to prevent the formation of ice and frost; and (b) salt crystals both with and without sand or cinders have been used for frost and ice prevention as well as for the removal of compacted snow.

These laboratory tests did not duplicate field conditions with regard to the effect of traffic, which is significant, and the actual process of formation of ice and frost as related to relative humidity and other changing weather factors. The general method used in testing for ice-melting capabilities was previously reported (9) except that larger quantities of distilled water were used. Also the melted ice at the prescribed test temperatures was measured at melting time intervals of 5, 10, 15, 30, 60, and 120 minutes, and also at 24 hours.

The ice-melting test data were first graphically plotted, and it was observed that the quantity of ice melted was related to the base 10 logarithm of the test time. By the method of least squares, a regression analysis was made of all ice-melting data. The resulting equations are given in Table 1. Care should be exercised when computing the depth of ice melted at time intervals of less than 5 minutes or greater than 24 hours. For time intervals of 5 minutes or less, the measurements were relatively inaccurate because the amount of melted ice was usually very small. The measurements generally did not extend beyond a 24-hour period.

As the data given in Table 1 show, the de-icing chemicals can melt a considerable depth of ice, given sufficient time. These laboratory results show sodium chloride at the laboratory test temperature to be greatly superior to calcium chloride. What this test does not demonstrate is the ability of a large crystal to "bore" through the ice and thus break up its structural properties so that chain action can accelerate its transformation into "slush." The slush can readily be plowed or otherwise removed from the pavement.

As indicated by the results of the regression analysis, the most apparent indication of ice-melting efficiency is the first constant in the equation, that is, the multiplier of

TABLE 1

DEPTH OF ICE MELTING BY DRY POWDERS

Temperature (deg F)	Chemical	n	Equation	Coefficient of Correlation	Standard Error of Estimate (in.)
10	Sodium chloride	4	$Y = 0.297 \log_{10}X + 0.234$	0.996	0.010
	Calcium chloride	4	$Y = 0.124 \log_{10}X + 0.221$	0.937	0.018
	Sodium formate	3	$Y = 0.270 \log_{10}X + 0.216$	0.977	0.023
	TKPP	5	$Y = 0.039 \log_{10}X + 0.069$	0.949	0.006
17	Sodium chloride	12	$Y = 0.185 \log_{10}X + 0.245$	0.925	0.049
	Calcium chloride	5	$Y = 0.161 \log_{10}X + 0.239$	0.992	0.009
	Sodium formate	12	$Y = 0.145 \log_{10}X + 0.206$	0.911	0.042
	TKPP	6	$Y = 0.062 \log_{10}X + 0.090$	0.953	0.010
	Urea	11	$Y = 0.074 \log_{10}X + 0.113$	0.854	0.026
24	Sodium chloride	12	$Y = 0.444 \log_{10}X + 0.467$	0.992	0.040
	Calcium chloride	12	$Y = 0.250 \log_{10}X + 0.347$	0.995	0.018
	Sodium formate	12	$Y = 0.412 \log_{10}X + 0.434$	0.997	0.023
	TKPP	12	$Y = 0.096 \log_{10}X + 0.145$	0.961	0.019
	Tripotassium phosphate	5	$Y = 0.147 \log_{10}X + 0.179$	0.993	0.008
	Sodium acetate	5	$Y = 0.146 \log_{10}X + 0.179$	0.988	0.001
	Urea	7	$Y = 0.212 \log_{10}X + 0.227$	0.993	0.014
	Sodium benzoate	4	$Y = 0.214 \log_{10}X + 0.199$	0.973	0.021

Note: Y = depth of ice melted, in., and X = time, hr. Chemical was spread at 0.25 lb/sq ft.

the time variable. In effect, this constant is the "slope" of the line, and also a mathematical definition of the rate of melting. The greater the numerical value of this constant is, the faster the ice melts. The "efficiency" of melting rate constants as given in Table 1 will also vary with the physical size of the grains of the chemical. It is believed that a grain of high bulk will continually be in physical contact with the ice interface, and the melting rate will be more rapid because of the high concentration of the chemical at this point. As a result, the ice-melting constants may be used not only to compare chemicals but also to evaluate the relative efficiency of various grain sizes for a particular chemical. The relative use of grain size of the chemical could be related to its use; for example, within limits, a small grain size may be more appropriately used for direct application to thin ice on the pavement surface. Conversely, a large grain could be used during the snow removal operation because it would bore through the thicker layer of snow more rapidly. In other cases, a mixture of fine and coarse grains may produce the best results.

Laboratory Ice Prevention Tests

In order to determine if the alternative chemicals could prevent the formation of ice, 34 concrete slabs were cast, each having a surface area of approximately 130 sq in. and depth of $2\frac{1}{2}$ in. These slabs were made from a typical 6-sack concrete mix design by using a local stock aggregate and 4.7 percent entrained air. Concrete was consolidated by means of vibration, and the surfaces of the slabs were given a surface texture similar to a typical in-service bridge deck. The tests were accelerated by moist curing the slabs for a minimum of 16 hours and then steam curing them for 17 hours prior to the application at the test solutions.

All slabs were identified and areas outlined on each slab surface for tests with the British Portable Friction Tester. Friction tests were performed initially on each slab by the conventional test method using water. After solutions were applied, these friction tests were performed on slabs that had been frozen and then allowed to warm to a temperature of about 45 F. The purpose of these tests was to determine what lasting effects, if any, the solution might have on skid resistance. The numerical results are not considered conclusive as there was difficulty in duplicating the measurements.

Six slabs were tested in each test set. In each set, one slab remained untreated as a reference or control slab. The concrete slabs were placed in the cold room for at least 16 hours before solutions were applied. Temperatures in the cold room varied from -10 to 0 F during the tests. De-icing chemical solutions were applied in the cold room by brushing them onto the slab surfaces. The slabs remained in the cold room for a minimum of 30 minutes after the solutions were applied. Before the slabs were removed, the visual condition of the surfaces was recorded and a temperature reading was taken on the control slab. The slabs were then moved to a humidity-controlled room where observations were made and recorded at short time intervals. After all slabs had thawed and the surface temperatures had reached approximately 45 F, the slabs were retested with the British Portable Friction Tester.

Three amounts of chemicals—0.5, 1.0, and 1.5 oz/sq ft—were applied on each set of slabs during subsequent tests. Results of tests indicated that the rate of application was critical for some chemicals, but not for others (Table 2). Most satisfactory at any rate of application were the TKPP solutions. They have relatively high specific gravities and are not quickly absorbed into the concrete or dried out through evaporation. Friction tests conducted in the lab did show some loss of skid resistance for the TKPP

TABLE 2

DE-ICING ABILITY OF CHEMICAL SOLUTIONS ON CONCRETE SLABS

Solution (oz/sq ft)	De-Icing Chemical	Percent Solution (by weight)	Temp (deg F)[a]		Application Rate (lb/sq ft)	British Portable Friction Readings[b]	
			Frost	Ice		Initial	After First Cycle
0.5	TKPP	60	+20	None	0.034		
	TKPP	30	+29	None	0.014	73	63
	TKPP + formamide	50-10	None	None	0.032		
	TKPP + formamide	25-5	+24	None	0.013	72	72
	Urea	20	+32	+32	0.007		
	Urea	40	+24	+20	0.015		
	Sodium chloride	10	+32	+28	0.004		
	Sodium chloride	25	+32	None	0.010		
	Form-urea-H_2O	75-20-5	+32	None	0.029		
	Form-urea-H_2O	50-40-10	+32	+15	0.019		
	Sodium benzoate	25	+32	+20	0.009		
	Sodium benzoate	37	+24	+10	0.014		
	Urea + calcium formate	17-8	+32	+28	0.008	70	70
	Calcium chloride	30	+30	None	0.013	69	71
	Magnesium sulfate	20	+31	+29	0.008	70	71
	Sodium formate	25	+32	None	0.010	66	60
	Plain slab	0	+32	None	0	62	60
1.0	TKPP	60	None	None	0.068	61	55
	TKPP	30	+29	None	0.028	70	53
	TKPP + formamide	50-10	None	None	0.063	67	61
	TKPP + formamide	25-5	+25	None	0.026	72	61
	Urea	20	+32	+30	0.014	72	73
	Urea	40	+28	+22	0.030	72	74
	Sodium chloride	10	+32	+22	0.008	69	70
	Sodium chloride	25	None	None	0.020	75	72
	Form-urea-H_2O	75-20-5	+31	None	0.058	52	54
	Form-urea-H_2O	50-40-10	+30	+5	0.040	65	62
	Sodium benzoate	25	+19	+6	0.018	72	68
	Sodium benzoate	37	+12	+4	0.028	68	65
	Urea + calcium formate	17-8	+32	+26	0.016	70	66
	Calcium chloride	30	+29	None	0.026	69	60
	Magnesium sulfate	20	+30	+24	0.016	70	61
	Sodium formate	25	+32	None	0.020	68	63
	Plain slab	0	+32	None	0	62	62
1.5	TKPP	60	None	None	0.102	61	50
	TKPP	30	+30	None	0.042	73	49
	TKPP + formamide	50-10	None	None	0.096	67	49
	TKPP + formamide	25-5	None	None	0.039	72	57
	Urea	20	+32	+20	0.021	72	73
	Urea	40	+30	+18	0.045	72	71
	Sodium chloride	10	+32	+17	0.012	69	75
	Sodium chloride	25	None	None	0.030	75	77
	Form-urea-H_2O	75-20-5	None	None	0.087	52	49
	Form-urea-H_2O	50-40-10	0	None	0.057	65	63
	Sodium benzoate	25	+20	0	0.027	72	68
	Sodium benzoate	37	+12	0	0.042	68	56
	Urea + calcium formate	17-8	+32	+12	0.024	70	66
	Calcium chloride	30	None	None	0.039	69	58
	Magnesium sulfate	20	+32	+15	0.024	70	56
	Sodium formate	25	+25	None	0.030	62	59
	Plain slab	0	+32	None	0	62	60

[a] Temperatures on the surface of the untreated slabs, above which no frost or ice formed on the chemically treated slab, for the first cycle.

[b] Each reading is the average of 3 test readings; slabs were all initially cooled to 0 F.

solutions; however, the test results for reasons previously mentioned were not considered conclusive. The main disadvantage of the British Portable Friction tests is the small area tested and poor reproducibility. For this reason, field tests were carried out using an ASTM-type towed trailer skid tester.

Field Skid Tests

Tetra-potassium pyrophosphate was found to be one of the more effective chemicals tested for the purpose of preventing ice formation on concrete. Thus, it was decided to implement a field testing program to determine its effect on the skid resistance of pavement.

Sections of approximately 200-ft lengths of concrete pavement were marked off for each test using the towed trailer skid tester. Each section of pavement was tested initially at a 40-mph speed by the conventional procedure, using water. Solutions of sodium chloride and tetra-potassium pyrophosphate were then sprayed at various rates of application and the sections retested for skid resistance. Both 30 percent TKPP and 60 percent TKPP solutions were used in addition to a 25 percent sodium chloride solution. Additional tests were run on sections with sand applied over the solutions. Three rates of application of solutions ranging from light to heavy were tested. The results of these skid tests are given in Table 3.

These tests were conducted on a concrete pavement surface that could be classified as fairly smooth and typical of the surfaces to be found on many bridge decks throughout the state. The average skid number of all test sections on which plain water was used was 46.8 for a trailer speed of 40 mph.

From the limited number of tests performed on this particular pavement surface, the following observations are noted:

1. Solutions of 60 percent TKPP at all application rates caused significant loss in skid resistance when no sand was applied to the pavement. It would not be recommended that this amount of solution be applied without sand. Only an application rate of less than 0.02 lb/sq ft at this 60 percent concentration might be suggested and this should be followed by a standard spread of sand. A standard spread of sand refers to the normal application rate now used by maintenance personnel.

TABLE 3

SKID TEST RESULTS

Concrete Pavement Section	De-Icing Chemical	Percent Solution (by weight)	Application Rate (lb/sq ft)	Sand Applied	Skid Number				
					With Water	With Solution			
						Immediately	After 0.5 Hr	After 1.0 Hr	After 1.5 Hr
1	TKPP	60	0.032	No	48.2	29.0	—	—	—
2	TKPP	60	0.022	No	46.3	30.9			33.8
3	TKPP	60	0.039	Yes, standard	46.3	38.6			39.0
4	TKPP	60	0.070	Yes, standard	45.8	35.7			37.6
5	TKPP	60	0.014	Yes, light	47.2	46.3			30.6
1	TKPP	30	0.012	No	48.2	44.3			70.7
2	TKPP	30	0.018	No	46.3	44.3			64.6
3	TKPP	30	0.034	No	46.3	44.3			48.7
4	TKPP	30	0.014	Yes, standard	45.8	48.2		55.0	
5	TKPP	30	0.018	Yes, standard	47.2	46.3		53.1	
6	TKPP	30	0.036	Yes, standard	50.1	46.3		47.2	
7	TKPP	30	0.057	Yes, heavy[a]	43.4	41.4	41.0		
9	TKPP	30	0.062	Yes, heavy[b]	47.7	40.5	43.4		
1	NaCl	25	0.010	No	48.2	57.0			67.2
2	NaCl	25	0.017	No	46.3	43.8			59.1
3	NaCl	25	0.025	No	46.3	44.3			46.3
4	NaCl	25	0.009	Yes, standard	45.8	48.2		54.5	
5	NaCl	25	0.017	Yes, standard	47.2	42.9		48.7	
6	NaCl	25	0.020	Yes, standard	50.1	40.5		41.9	
7	NaCl	25	0.036	Yes, standard	53.4	42.9	42.9		
9	NaCl	25	0.042	Yes, standard[b]	47.7	43.4	47.2		

[a] After solution was applied.

[b] Before solution was applied.

2. Solutions of 30 percent TKPP showed much more promising results. Without sand, only small decreases in skid resistance occurred. A standard application of sand broadcast over the solutions increased skid resistance. Use of a 30 percent solution concentration is proposed, the rate of application dependent on existing concrete and climatic conditions. A standard spread of sand should be applied in conjunction with the solution.

3. Solutions of 25 percent sodium chloride (saturated concentration) were tested for comparative results. Skid numbers quite similar to the 30 percent TKPP solutions were obtained on tests run immediately following application of the chemicals.

A significant observation was made during these field tests. All TKPP solutions remained longer on the pavement surface than did sodium chloride solutions. Sodium chloride solutions were more readily absorbed into the concrete or lost because of evaporation. This ability of TKPP solutions to remain longer on the surface may be an important feature in that the de-icing ability is probably extended over a longer period of time.

After test sections sprayed with the TKPP solutions had eventually dried, the pavement was covered with a white deposit, suggesting that perhaps the de-icing ability of the solution would be restored if the surface were rewet with water, frost, snow, or ice.

Laboratory Concrete Tests

To determine if the chemicals could adversely affect concrete, we subjected 84 cylinders ($4\frac{1}{2}$ by 9-in.) with gage plugs at each end to various tests. The cylinders were made from 2 mix designs: (a) $4\frac{1}{2}$ sacks of cement per cubic yard at $2\frac{3}{4}$-in. slump and 5.8 percent entrained air, and (b) 7 sacks of cement per cubic yard at 4-in. slump with 4.5 percent entrained air. All cylinders were cured for a minimum of 28 days by complete immersion in tap water at room temperature, then oven-dried at 140 F for 28 days in a forced-draft oven. One test alternately immersed 42 of the cylinders in a saturated solution of the chemical for 7 days, and then subjected them to oven-drying at 140 F for 7 days. Changes in length were measured after each cycle by means of a comparator. The results of the length change measurements after 8 cycles of alternate immersion testing are shown in Figures 1 through 6. Weight measurements were made at similar times along with periodic observations and photographs. The other 42 specimens were partially immersed to a depth of 2 in. in the various solutions.

The following is a summary of the results:

1. Both $4\frac{1}{2}$- and 7-sack concrete cylinders are not significantly affected after 7 cycles of wet-dry tests in tap water.

2. Sodium formate caused severe deterioration of both $4\frac{1}{2}$- and 7-sack concrete specimens. Visible surface scaling was evident after only 2 cycles. Figure 7 shows the condition of $4\frac{1}{2}$-sack concrete specimens after removing them from solutions at the completion of the wet portion of the fourth cycle. Crystal growth and severe disintegration are obvious. Only one more cycle was possible before terminating tests employing sodium formate because of the extreme disintegration of the concrete.

3. Concrete cylinders cycled in a saturated sodium chloride solution were first observed to have scaling of the surfaces of all cylinders after the third cycle. This scaling did not become severe through 7 cycles and is believed to be primarily confined to the surface area and not of major concern yet to the structural strength of the concrete. The distress observed is similar to that occurring in normal air-entrained concrete exposed to similar salt concentrations.

4. Thus far, observations of the test with the saturated solution of tetra-potassium pyrosphosphate have not revealed any noticeable detrimental effect on concrete after 3 cycles; however, not enough data are available at this time to make any conclusions on the long-term effect of the chemical.

Figures 7, 8, and 9 show the appearance of $4\frac{1}{2}$-sack concrete after 4 cycles of alternate immersion and oven-drying. Figures 10 and 11 show the amount of concrete disintegration after 5 and 6 cycles of alternate immersion in sodium formate for the $4\frac{1}{2}$- and 7-sack concrete.

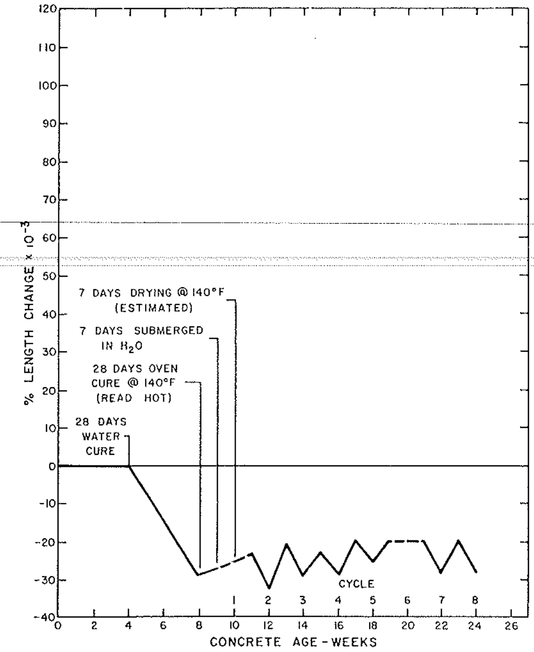

Figure 1. Alternate immersion tests of 4½-sack concrete in tap water.

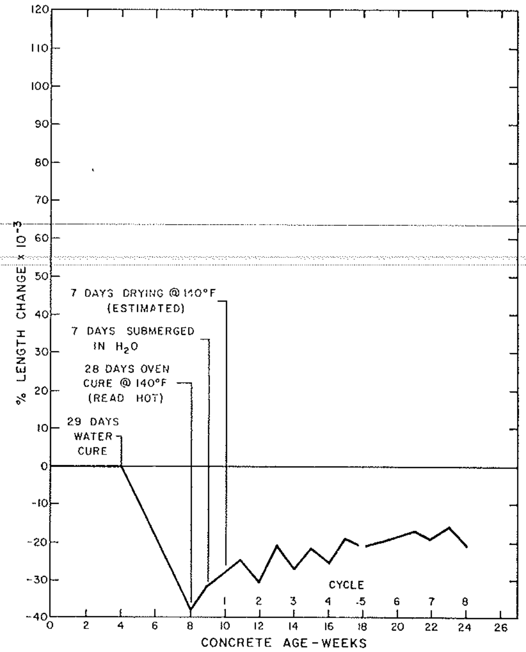

Figure 2. Alternate immersion tests of 7-sack concrete in tap water.

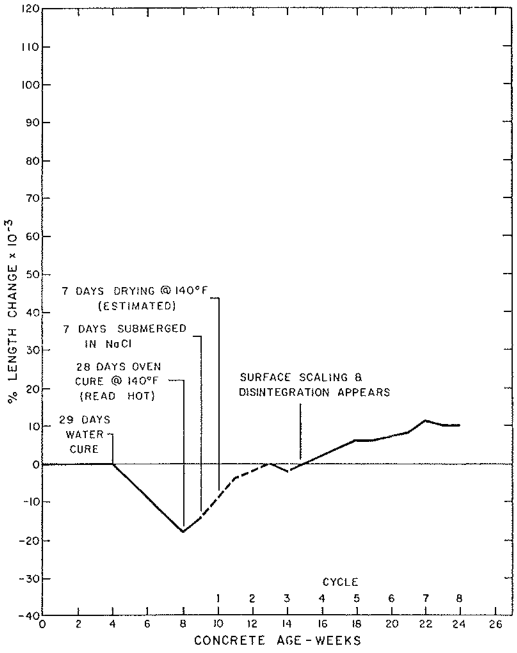

Figure 3. Alternate immersion tests of 4½-sack concrete in sodium chloride solution.

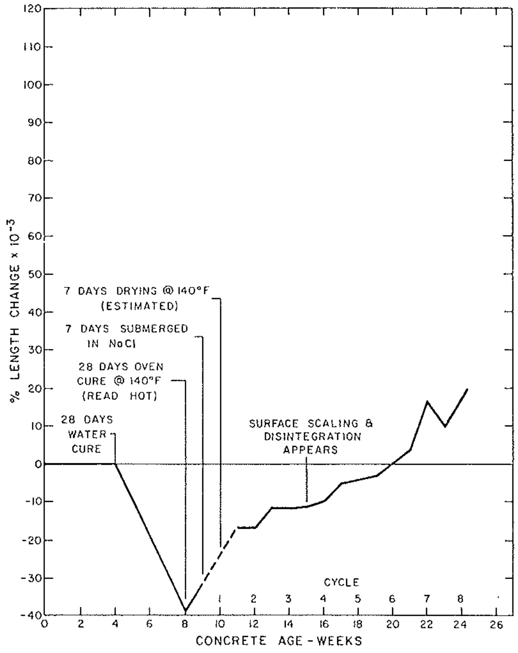

Figure 4. Alternate immersion tests of 7-sack concrete in sodium chloride solution.

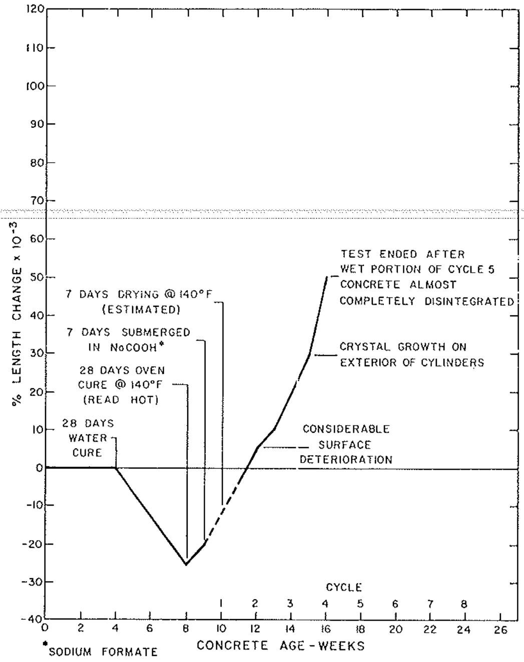

Figure 5. Alternate immersion tests of 4½-sack concrete in sodium formate solution.

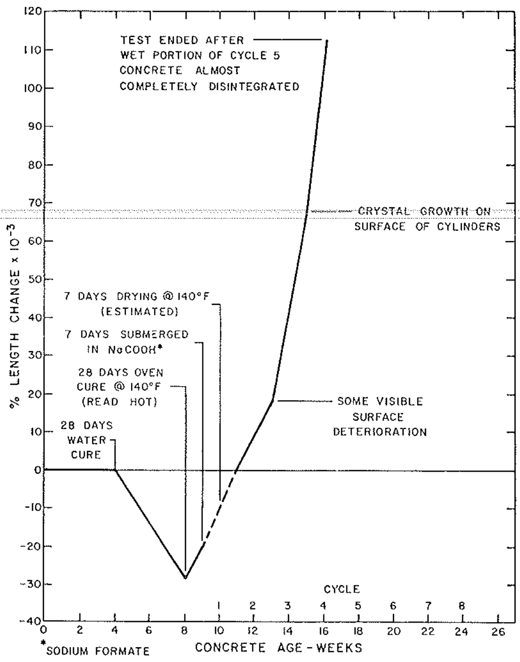

Figure 6. Alternate immersion tests of 7-sack concrete in sodium formate solution.

Corrosion Tests

One of the most important properties of any de-icing chemical considered as a substitute for sodium chloride is that it be noncorrosive to reinforcing steel in bridge decks, or at least only slightly corrosive. A simple corrosion screening test was chosen to evaluate the corrosivity of the various concentrations of chemical solutions. The method used was to immerse mild steel corrosion probes in the solutions and measure the corrosion rate of the steel by means of the change in the electrical resistance of a thin metal strip. The resistance change is caused by any loss in metal cross section as corrosion proceeds. The equipment used is shown in Figure 12.

Figure 7. Condition of 4½-sack concrete after 4 cycles of alternate immersion in sodium formate and oven-drying.

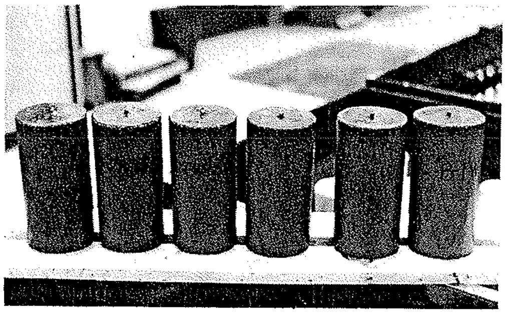

Figure 8. Condition of 4½-sack concrete after 4 cycles of alternate immersion in tap water and oven-drying.

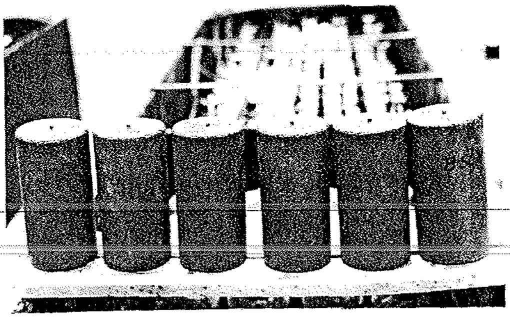

Figure 9. Condition of 4½-sack concrete after 4 cycles of alternate immersion in sodium chloride and oven-drying.

Figure 10. Condition of 4½-sack concrete after 5 and 6 cycles of alternate immersion in sodium formate.

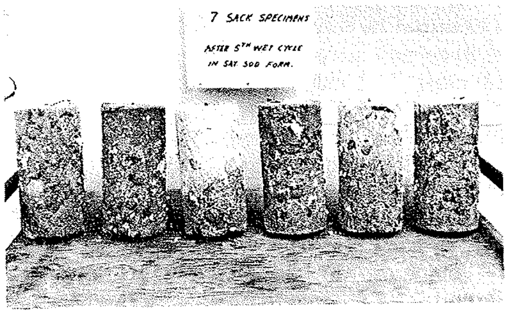

Figure 11. Condition of 7-sack concrete after 5 and 6 cycles of alternate immersion in sodium formate.

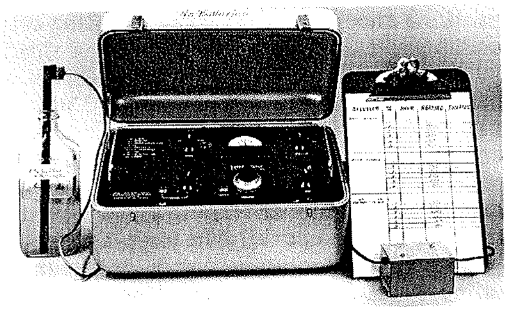

Figure 12. Corrosimeter testing apparatus.

Upon completion of each corrosion test, the pH of each solution was determined. Some of the results of corrosion and pH tests are given in Table 4. The corrosion tests were run on each chemical when dissolved in distilled water and also in lime-saturated distilled water. Tests using lime-saturated water are believed to simulate conditions found in concrete where the pH of salt-free concrete is about 12 or 13. The corrosion test probes were normally submerged in each test solution for 3 days. Corrosion rate for the probe immersed in distilled water was 7.2 mils per year. For the probe immersed in the lime or calcium hydroxide solutions, the rate was 0.6 mils per year.

TABLE 4

CORROSION TEST RESULTS

Percent Solution (by weight)	Solutions in Distilled Water								Solutions in Lime-Saturated Distilled Water							
	Sodium Chloride		Urea		Sodium Formate		TKPP		Sodium Chloride		Urea		Sodium Formate		TKPP	
	Mils	pH	Mils	pH	Mils	pH	Mils	pH	Mils	pH	Mils	pH	Mils	pH	Mils	pH
1	1.6	7.2	6.6	7.2	2.0	8.4	0.5	9.5	1.5	11.6	3.8	12.0	3.1	11.7	0.3	12.3
2	1.5	7.1	1.9	7.2	2.9	7.2	1.2	9.5	4.5	11.4	0.6	12.4	0.6	11.6	0.4	12.6
4	1.6	7.0	2.6	7.6	1.8	7.4	1.3	9.4	3.6	11.2	0.0	12.5	0.5	11.3	1.0	12.3
8	1.1	6.9	6.5	7.6	1.4	7.5	3.7	9.4	2.6	10.9	0.2	12.2	0.7	11.2	0.7	12.1
16	2.1	6.9	5.4	7.8	1.0	7.6	4.0	9.3	2.6	10.9	1.4	12.3	0.3	11.2	0.5	12.3
30	1.0	7.0	3.9	8.0	0.0	7.6	0.8	9.5	0.0	10.2	—[a]	12.3	0.0	10.8	0.4	11.8

[a] Reading not obtained because of damaged probe.

Note: Mils is corrosion rate in mils per year and pH is hydrogen-ion concentration after test.

Some important observations from these corrosion tests are (a) no completely noncorrosive de-icing chemical has been tested; (b) tetra-potassium pyrophosphate produced the most promising results when tested in lime-saturated water solution insofar as a minimum corrosion rate was observed; (c) sodium chloride solutions in lime-saturated distilled water gave higher corrosion rates than corresponding solutions in plain distilled water (this occurred at 2, 4, 8, and 16 percent solutions); and (d) urea and sodium formate solutions in lime water at 1 percent concentrations were found to be fairly corrosive but almost noncorrosive at all higher concentrations.

Ecology and Toxicity

Recently there has been quite an increase of interest in the effect of de-icing salts on plant life (10, 11, 12). As a result, this investigation of alternative de-icing chemicals also included emphasis on the effect of these new materials on the ecology. Several agencies and individuals were asked to comment on various chemicals. Only a few of the many comments received will be discussed in this report.

Toxicity—In a private communication, a representative of the California State Environmental Health and Consumer Protection Program has related that the same precautions should be used when handling tetra-potassium pyrophosphate as is used for sodium and calcium chloride. Urea should not have any adverse effect on humans.

Ecology—In a private communication of September 3, 1969, with the College of Agriculture, University of California, Davis, a professor stated that in the East sodium and calcium chloride have resulted in soil conditions that are toxic to most plants. Urea should not cause any toxicity to plants unless used in large quantities, although it might stimulate an undesirable growth along the highway. Tetra-potassium pyrophosphate should give the least trouble from a residue standpoint because it should be tied up by the soil and be unavailable for plants.

In a private communication of November 4, 1969, from the regional forester's office of the Forest Service, U.S. Department of Agriculture, an opinion was offered that urea could leach into streams and lakes and cause an increase in algae or other aquatic plant growth. It was also stated that urea or tetra-potassium pyrophosphate would not be as damaging to the roadside environment as the calcium and sodium chlorides.

In a written communication of July 28, 1969, from the Soil Conservation Service, U.S. Department of Agriculture, an opinion was given that extremely high concentrations of urea would kill all plants next to the roadway, but the greatest hazard is to streams and lakes wherein it could greatly increase plant growth and add to pollution. The opinion was also given that tetra-potassium pyrophosphate would be the least hazardous to plants, and it adds little to the pollution problem because it would be applied to normally acid soils where snow and ice occur and would thus be fixed by the soil.

Consideration should also be given to the influence of nitrogen compounds on the nitrate buildup in ground water. Currently, the California State Department of Public Health is studying the toxic effects on infants under 6 months of age of nitrates in drinking water from wells (14).

Discussion of Research

The studies of alternative de-icing salts are not complete. Many chemicals that have been tested in one phase of the program have not been tested in other phases. The reason is that it is most urgent to find a relatively noncorrosive salt at a reasonable cost at the earliest date.

During the investigation, sodium formate had an ice-melting capability that was nearly equal to the chlorides. However, it was found in the alternate immersion tests that concrete would be rapidly attacked. Rather than continuing the testing of this chemical, which would necessarily include finding means of offsetting its aggressiveness to concrete, we diverted attention to other chemicals that did not exhibit this characteristic. We intended to retrace and continue some of the research steps with some of the less costly de-icing chemicals if the alternative chemicals do not fit all requirements. However, this would probably mean testing many combinations of chemicals and that type of investigation does not usually give rapid results.

Urea and tetra-potassium pyrophosphate appear to be among the better candidates tested as alternative de-icing chemicals. However, they may need to be modified to reduce corrosivity to steel. We believe that the phosphate may be mixed with lime and thus be rendered relatively noncorrosive to steel. However, we anticipate that the lime-phosphate mixture will still be somewhat corrosive to zinc and aluminum.

Our tests show that urea in water is corrosive to steel and, at certain concentrations, it appears to be more corrosive than salt (13). The combination of urea, lime, and water significantly reduces the corrosive action to steel. However, there is some concern about the corrosive properties of urea on bridge decks that have cracked concrete and its possible effect on plant life. Urea is a nitrogen compound, and, coupled with the soil in the cracks, it could possibly be reduced by bacterial action to highly corrosive nitrates. Also, urea and other nitrogen compounds could offer the greatest hazard in stimulating algae growth in adjacent streams. Because of possible effects on the environment, controls may be necessary to govern the use of fertilizer types of materials in certain geographic areas.

ACKNOWLEDGMENT

The work on de-icing chemicals was performed in cooperation with the Bureau of Public Roads, Federal Highway Administration, U.S. Department of Transportation. The work was performed under the direction of R. F. Stratfull who was also helpful in the preparation of this report. The opinions, findings, and conclusions expressed are those of the authors and not necessarily those of the Bureau of Public Roads.

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Informal Discussion

William N. Records

The Bureau of Public Roads is a cosponsor of this research on bridge deck icing. We are sponsoring and cosponsoring a number of research projects on preferential bridge deck icing. We have come to realize that all of these projects are based on the premise that bridge decks do experience preferential icing on many occasions and that, when this occurs, they have accident rates significantly higher than those of other sections of roadways. Unfortunately, we do not have any facts to prove this premise. We would like to know whether anyone has any facts that show the relative occurrence of preferential bridge deck icing and the accident rates on these bridge decks.

Lawrence H. Chenault

What was your experience with heated bridges, that is, the enclosed insulated area without heat, and what was the actual effective cost and performance of the heated areas?

Don L. Spellman

The heated portions did defrost more effectively. The unheated and enclosed sections did not show any improvement over those left open. There was quite a time lag between the time we turned on the heat and the time the deck surface temperature began to rise, but this was probably due to the fact that we were using air in a convection system. We also tried heating a metal deck bridge. We have an orthotropic bridge in which we installed a gas heater for this purpose. Unfortunately, we have had little frost form on this bridge during the past 2 winters so we do not have a great amount of experience.

Glenn G. Balmer

What did you use for sealing the bridge deck? Do you have evidence that it prevented penetration of your anti-icing agent?

Spellman

We are trying several different bridge deck sealant systems now on a full scale, including not just epoxy type sealants but also rubber. Four were reported on here at this Symposium. What we are trying to find out is what evidence do we have that the sealants are not leaking. We are doing some laboratory testing by compacting various types of AC mixes over sealants because we are going to overlay these seals with a wearing course. The overlay will probably be an ordinary plant mix surfacing, but there is also an epoxy asphalt concrete that looks very good and can be put down in a much thinner layer. This makes our bridge people happy because they do not have as much dead load to deal with. We have compacted various mixes over these membranes and then tested them for permeability, and we do get puncturing when we use large rock ($^{3}/_{4}$ in.) but not when we use small ($^{3}/_{8}$ in.) rock. It appears that when we use the smaller gradation we do not get any puncturing of the membrane. We are testing for leakage by permeability.

Thad M. Jones

Do you think that, if there is a high likelihood of frost occurring, an hour's advance warning would be adequate to get your crews out?

Spellman

Not always, because they would have to be on standby, waiting in the maintenance station on weekends. An hour certainly would not give them time to cover the number of miles that they have to cover and do their work.

Jones

This would be on a selective basis because all bridges would not ice simultaneously.

Spellman

How are we going to know which ones will ice first? I think it is possible to establish areas of finite sizes, put an ice detection system on the worst bridge, find out which one usually ices first, and use that as a guide to cover the area, maybe a hundred square miles, depending on the geographical layout.

Jones

I had particular reference to the system used in the United Kingdom in which an individual warning device on bridge approaches or on the bridge deck activates an alarm in the central station indicating that a particular bridge is in an incipient icing condition and that if the temperature falls 1 or 2 deg it will have frost.

Spellman

You mean have a warning device on every bridge?

Jones

That would be nice.

Spellman

That would work as an alternative. We felt that we could do our maintenance work with long-lasting chemicals. Incidentally, this chemical I mentioned is fairly sticky. It is amazing how long it will stay in contact with the concrete and remain effective. We spread it on one bridge and 2 weeks later the maintenance people reported that the part that was sprayed had no frost or ice on it and the other part did. So our approach has been to have the maintenance people put this chemical on during their regular working hours and to avoid trying to guess when the frost is going to occur.

A Brief Review of Snowdrifting Research

Malcom Mellor

The blowing-snow phenomenon is described, and practical procedures for controlling deposition of windblown snow are reviewed. Field methods are given for measuring velocity, particle concentration, mass flux, particle size, and their distributions with respect to height. The analysis of steady-state wind transport over a plane surface is outlined, and difficulties in extending the treatment to cover complex flow perturbations are stressed. Wind tunnel studies are reviewed, and modeling criteria for snowdrift simulation are given. Suggestions for future work include semi-empirical model and prototype studies for short-term benefits, and extension of fundamental analyses and field observations for progress over the long term.

Without delving too far into antiquity, it is safe to say that research on windblown snow and snowdrift control began at least a century ago. However, research efforts during this period have been sporadic and progress has been slow.

Basic control measures such as snow fences and shelter belts evolved without systematic research effort, but a significant improvement in understanding came with Finney's pioneering wind tunnel studies, which provided results that still have not been superseded. Finney's simple techniques were followed in a number of subsequent studies, but in recent years professional hydrodynamicists have attempted to apply more rigorous modeling criteria. The latter efforts have undoubtedly clarified understanding of wind-tunnel modeling, but so far they do not appear to have produced practical results that are significantly better than those yielded by simpler studies. The reason for this is that there has been a tendency for wind tunnel specialists to be supplied with inaccurate information on the natural phenomenon.

More fundamental research on the phenomemon of snow transport by the wind made little headway until about 20 years ago, but there is now an appreciable amount of useful observational data and a fairly clear understanding of the processes involved. Steady-state snow transport across flat unobstructed surfaces can be treated analytically, but effects of flow perturbations on snow transport and deposition have received virtually no attention theoretically.

From the engineering point of view, present day needs are being met largely from long-established technology. Over the short term, improvements in control measures will have to be achieved by semi-empirical developments based on model tests and field tests, but in recent years attempts to refine modeling techniques have been frustrated by lack of reliable input data. It therefore seems imperative to blend together fundamental and technical investigations, which previously have tended to follow independent paths with a minimum of interaction.

This brief review is intended to outline present ideas on basic mechanisms of snow transport and to relate them to engineering research on snowdrift control measures. It includes a digest of data that might form a basis for the formulation of realistic modeling criteria. The review does not cover the most recent Russian references, which are not yet available in English translation.

SURFACE WINDS

As wind blows across flat ground, surface drag creates a velocity gradient normal to the surface. When wind speed is a few m/sec turbulence begins to develop, and when it exceeds 10 m/sec turbulence is usually fully developed.

With strong winds and the neutral stratification typical for snowfields, there is a logarithmic relationship between wind velocity u and height above ground z, at least in the lower layers where blowing snow occurs.

$$u = (u_*/k) \ln(z/z_0) \tag{1}$$

where u_* is a parameter termed the "friction velocity" (typically 3 to 4 percent of the wind velocity at 10-m height, u_{10}), k is von Karman's constant ($\approx$0.4), and z_0 is a surface roughness parameter (~0.1 to 1.0 mm for typical snowfield conditions). With strong winds, typical snow surfaces are aerodynamically rough (no laminar sublayer). When field measurements of u are plotted against log z, the intercept and slope give z_0 and u_* respectively.

The eddy viscosity, or momentum exchange coefficient for turbulent mixing, K, can be expressed as:

$$K = k\, u_*\, z \tag{2}$$

SNOW PARTICLES

Freshly precipitated snow crystals vary widely in size, shape, and mass according to the weather conditions prevailing during their nucleation and fall. By contrast, snow particles picked up from the surface, or maintained in turbulent suspension by strong winds, tend to be simple equant particles whose sizes are controlled within fairly narrow limits by the wind characteristics. For present purposes, interest centers on size, mass, and fall velocity of airborne snow particles.

Measurements on freshly precipitated snow particles by Nakaya and Terada (33), still generally accepted, given the following values for terminal fall velocity w: spatial dendrites, 57 cm/sec; plane dendrites, 31 cm/sec; "powder snow," 50 cm/sec; w is independent of size in all 3 cases. For needle crystals, w increased from $\approx$20 to $\approx$70 cm/sec as length increased from 1 to 2 mm. For graupel, w increased from $\approx$120 to $\approx$260 cm/sec as size increased from 1.5 to 5 mm, and rimed crystals fell at $\approx$100 cm/sec. Generally higher values of w were found for very small crystals by Mellor (31): spatial dendrites 0.2 to 1.0 mm, 70 to 90 cm/sec; plane dendrites $\leq$ 1 mm, 45 to 100 cm/sec; needle crystals 0.5 to 2 mm, 50 to 100 cm/sec; rimed crystals 0.2 to 1 mm, 50 to 105 cm/sec; w tends to increase with size in the last 2 cases. (The Japanese results were for particles falling through an enclosure, whereas Mellor's results were for particles falling en masse in open air.)

Fall velocities of snowflakes (aggregations of crystals) measured by Magono (27) were in the range 80 to 240 cm/sec, with w tending to increase as size increased from 0.2 to 4.5 cm. Langleben (23) related w (cm/sec) for a snowflake to the diameter of the water drop formed by melting it d (cm).

$$w = C_1 d^a \tag{3}$$

where a = 0.31 and C_1 ranges from 160 to 234 for different types of snow. Litvinov (26) obtained results indicating a $\approx$0.16 and C_1 equal to 87 and 115. For small snowflakes ($\approx$1 cm) Mellor (31) found w mainly in the range 70 to 140 cm/sec; a frequency distribution showed $70 \leq w \leq 80$ cm/sec to be most common for typical midwinter snowfalls at Hanover, New Hampshire.

Nakaya and Terada (33) related the mass of a snow crystal m (mg) to its maximum linear dimension d (mm).

$$m = C_2 d^a \tag{4}$$

where C_2 and a are respectively 0.0038 and 2 for plane dendrites, 0.027 and 2 for rimed plates and stellar dendrites, 0.010 and 2 for powder snow and spatial dendrites, 0.0029 and 1 for needles, and 0.065 and 3 for graupel. Other values of m for a variety of small crystals are given in Table 1.

TABLE 1

ESTIMATED PARTICLE MASS FOR FRESH SNOW

Snow Type and Size (mm)	Approximate Mean Particle Mass (g)
Spatial dendrite, 0.3 diameter	1.47×10^{-5}
Spatial dendrite, 0.2 to 0.5 diameter	5.5×10^{-6}
Spatial dendrite, 0.8 diameter	4.29×10^{-5}
Rimed grains, 0.2 diameter	7.99×10^{-6}
Rimed grains, 0.1 to 0.7	7.63×10^{-6}
Spatial dendrites, 0.5 diameter	3.07×10^{-5}
Rimed spatial dendrites, 1	4.52×10^{-5}
Rimed plane dendrites, 1 to 2	5.49×10^{-5}
Hexagonal "flowers" (plane dendrites with plates on arms), 1 diameter	2×10^{-6}
Stellar dendrites, 1	1.5×10^{-6}
Stellar dendrites, 1 to 2 diameter	5×10^{-6}
Needles, 2 long and 0 to 1 thick	1.4×10^{-5}

Particles picked up from the surface or particles falling into turbulent windstreams are reduced to simple equant forms by mechanical action and vapor diffusion; particle mass m is related to particle diameter d by

$$m = C_3 \rho_i d^3 \tag{5}$$

where $C_3 \sim 1$ and ρ_i is the density of ice (0.917 g/cm^3). Size selection is determined largely by upward eddy velocities in the turbulent windstream. Under typical strong wind conditions, mean particle size is $\approx$0.07 to 0.1 mm above 10-cm height (25, 8, 7) and somewhat larger in the lowest layers next to the surface. Size distribution of blown snow particles is discussed in detail by Budd (7) and a data summary is given by Mellor (30).

Terminal fall velocity (w, cm/sec) of equant snow particles from 0.1 to 1.5 mm effective diameter (d, mm) was measured by Mellor (29), who found:

$$w = C_4 d \tag{6}$$

where C_4 is 166, 191, and 223 for angular, subangular, and rounded particles respectively. Budd (7) estimated w for blown snow particles from empirical relationships for other atmospheric particles, taking $C_4 = 388$ for spherical particles and $C_4 = 244$ for irregularly shaped particles.

INTERACTION OF SNOW AND WIND

Snow can be moved horizontally by the wind in a number of ways.

Snowfall With Light Winds

When new snow is falling at 1 m/sec or less, wind speeds of a few m/sec impart appreciable horizontal travel, even when turbulent suspension is negligible. The horizontal mass flux q_H is related to vertical mass flux q_V (snowfall rate, accumulation rate), wind speed u, and particle fall velocity w by

$$q_H/q_V \approx u/w \tag{7}$$

Direction to the particle velocity vector is also given by u/w.

Turbulent Diffusion

In a fully turbulent boundary layer, snow particles can be held in suspension indefinitely, upward transport in turbulent eddies counteracting gravity settlement. The snow particles are small, well dispersed, and have low inertia, so that the problem can be approached from general turbulent diffusion theory.

By considering a wide turbulent flow across a long plane surface and by assuming that (a) steady-state conditions prevail (concentration at any level invariant with time) and (b) gradients of velocity and concentration along the flow direction are small compared with normal (vertical) gradients, the diffusion equation reduces to

$$vn - \epsilon_z(\partial n/\partial z) = 0 \tag{8}$$

where v is the component of particle velocity in the z (vertical) direction, n is particle concentration (mass of snow per unit volume of air) at height z, and ϵ_z is a mass transfer coefficient (eddy diffusivity) in the z-direction. If it is further assumed that (a) v is equal to snow particle fall velocity w and w is invariant with height z, (b) horizontal particle velocity is equal to wind velocity u (no "slip"), and (c) ϵ_z is equal to the eddy viscosity for turbulent winds K (Eq. 2), then the required solution of Eq. 8 is

$$n/n' = (z/z')^{-w/ku_*} \qquad (9)$$

where the prime denotes a fixed reference level. It we substitute for u_* from Eq. 1, snow concentration n can be expressed in terms of wind speed u.

$$\ln(n/n') = -(w/k^2) \times \ln(z/z_o) \times \ln(z/z') \times (1/u) \qquad (10)$$

Equation 9 is quite realistic when the reference height z′ is chosen at a low level, especially for strong wind conditions and for considerations of transport close to the surface. However, observations show w tends to increase with u, and also to decrease with increasing z; hence basic theory ought to be modified to account for nonuniform particle size (7, 8, 38). For present purposes the simple theory for uniform particle size is preferable, as it illustrates fundamental relationships without undue complication or much loss of reality.

The horizontal mass flux of snow q at any height z is

$$q = n\,u \qquad (11)$$

and the rate of snow transport per unit width of the flow Q between 2 given levels z_1 and z_2 is

$$[Q]_{z_1}^{z_2} = \int_{z_1}^{z_2} n\,u\,dz \qquad (12)$$

Saltation

The term saltation was used by Bagnold (1) to describe a transport mechanism for blown sand; particles were envisaged as bonding along the surface impelled by wind, elastic impacts with the surface causing particles to bounce and to dislodge other particles. Following early studies of saltation for snow (32, 16), Radok (38) applied Owen's saltation theory (37) to snow, using field data to define probable characteristics of the saltation layer. Trajectories of saltating snow particles were photographed by Oura et al. (1967).

The following picture emerges from Radok's analysis (38). Snow particles plucked from the surface by hydrodynamic forces stream along under gravitational and wind shear forces in a layer whose self-regulating thickness is governed only by the surface shear stress. Saltation is initiated at relatively low wind speeds, and the saltation layer is maintained even when turbulent diffusion develops with increasing wind speed. Snow concentration in the saltation layer remains of the same order of magnitude, irrespective of wind speed. Deposition and erosion take place by vertical flux through the saltation layer, but are not directly controlled by saltation. The saltation layer affects the airflow above it as would fixed roughness elements of comparable height; its effective roughness tends to decrease with increasing wind speed as a consequence of its upper boundary becoming more diffuse due to increased particle flux.

Threshold conditions for onset and maintenance of saltation, determined by the surface shear stress, may be defined in terms of a dimensionless group $\gamma = (\rho_a u_*^2/\rho_p g\, d)$, where ρ_a and ρ_p are densities of air and particles respectively and d is particle diameter. Saltation over a loose surface is initiated when $\gamma \approx 10^{-2}$, and ceases when $\gamma \approx 0.0064$; free-stream velocities corresponding to these values are ≈ 2.5 and ≈ 2.0 m/sec respectively when d = 0.1 mm. When $\gamma > 1.0$, all particles of size d will be carried into suspension. Thickness of the saltation layer is $\sim(u_*^2/2g)$, and concentration stays roughly constant at the same order as the fluid density ($\sim 10^3$ g/m^3). Thus the mass flux of the saltation layer is proportional to u_*^3. Radok found the saltation layer thickness increasing from $27z_0$ to $113z_0$ as u_{10} increased from 5 to 20 m/sec; the height of fixed roughness elements is commonly found to be $20z_0$ to $30z_0$.

MEASURING WINDBLOWN SNOW

The prime object in measuring windblown snow is to measure concentration n, mass flux q, and velocity u as functions of height z, covering a representative range of free-stream wind speeds u_{10}.

Direct Methods

Direct methods measure horizontal mass flux q by extracting snow particles from a cross section of the airstream at a given height, the total catch for a timed period being weighed to find the mass passing unit cross section in unit time. Measurement of average wind speed u at the same height and time permits concentration n to be calculated. This method gives temporal means of q, n, and u rather than instantaneous values, which is preferable for a turbulent flow.

Several types of snow traps were evaluated by Budd et al. (8), who determined aerodynamic and collection efficiencies from wind tunnel tests and field tests. The simple trap shown in Figure 1 was found suitable for general field studies; its characteristics are such that the catch is about 10 percent too high, but in practice losses during handling and weighing tend to reduce this error.

Indirect Methods

Indirect methods for measuring snow concentration are based mainly on attenuation of electromagnetic radiation passing from a source to a detector through the snow-filled airstream. Visible light techniques seem to have developed furthest (45, 22, 14), but alpha, beta, and gamma radiations have been investigated (30). Although electromagnetic metering is highly attractive, reliable equipment for operational use is not yet available.

CONCENTRATION AND FLUX OF BLOWING SNOW

Reliable data on concentration and flux are rare. The only comprehensive program of field measurements by experienced investigators using thoroughly tested and calibrated gages appears to be a "third generation" study by Budd, Dingle, and Radok (8).

Concentration and Flux as Functions of Height

Simple turbulent diffusion theory (Eq. 9) gives a power relation between concentration (or density) n and height z. Substitution of appropriate values for w and u_*

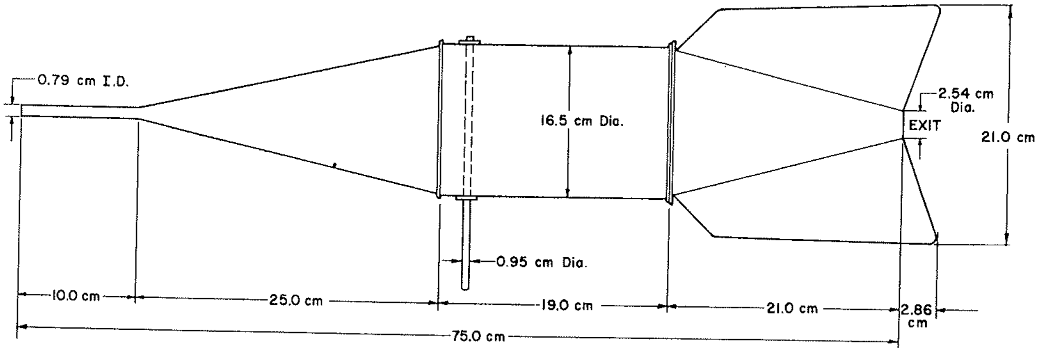

Figure 1. A simple trap for measuring concentration and horizontal flux of blowing snow. Several of the traps are mounted on a mast, with anemometers alongside, so as to give vertical profiles of n and q.

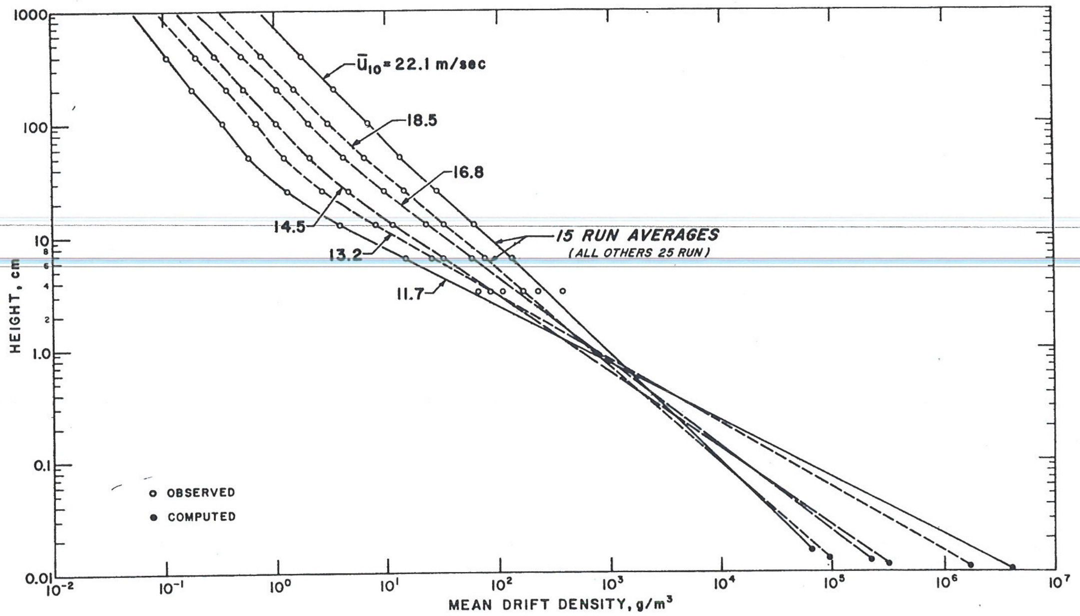

Figure 2. Vertical profiles of mean drift density, or concentration, for a range of wind speeds (8).

indicates that for strong winds the exponent is ≈ -1. Field data (Fig. 2) confirm this prediction for $u_{10} \approx 20$ m/sec, but for lower wind speeds n changes more rapidly with z for $z < 50$ cm. The measured profiles converge at $z \approx 1$ cm, giving $n \approx 10^3$ g/m^3 for all wind speeds, in agreement with saltation theory.

Field data show a similar power relation between flux q and height z in strong winds, with a corresponding trend to more rapid change of q with z at low levels in gentler winds. Because u can be expressed as a power of z, with an exponent $\approx 1/7$ for neutral stability, simple theory (Eq. 9) predicts that q (= nu) will be proportional to a power of z.

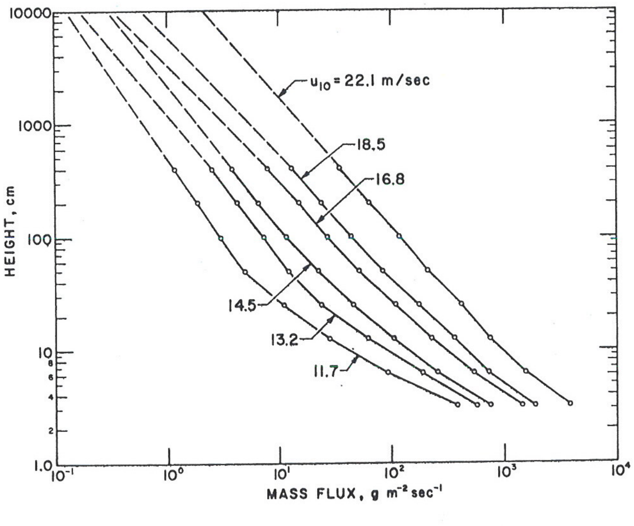

Figure 3. Vertical profiles of mean horizontal mass flux for a range of wind speeds (8).

Concentration and Flux as Functions of Wind Speed

Equation 10 predicts a linear relation between log n and 1/u for a given value of z, provided that w and z_0 are invariant with u. Extensive field data by Budd et al. (8) were quite well represented by such a relation (Fig. 3); lines fitted to their data are shown in Figure 4, which shows representative values of n as a function of u with z as parameter. It may be noted that n becomes less dependent on u as z drops below 10 cm. Because $(1/u) \ln (z/z_0)$ is proportional to $1/u_{10}$, a similar relationship between n and u_{10} can be expected; Figure 5 shows data bands for n as a function of u_{10} using results from 3 different stations.

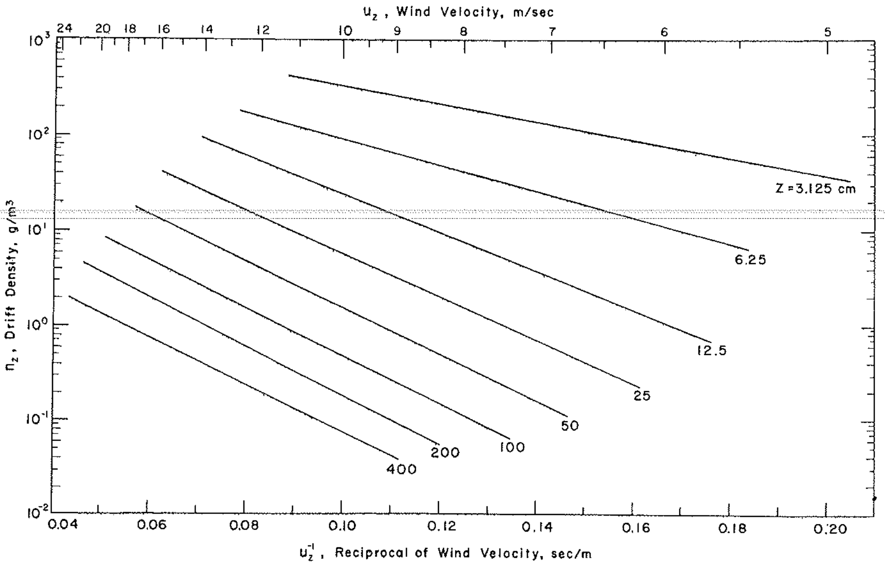

Figure 4. Observed relationships between mean drift density, or concentration, and wind speed for a range of heights. Data points have been omitted for clarity (8).

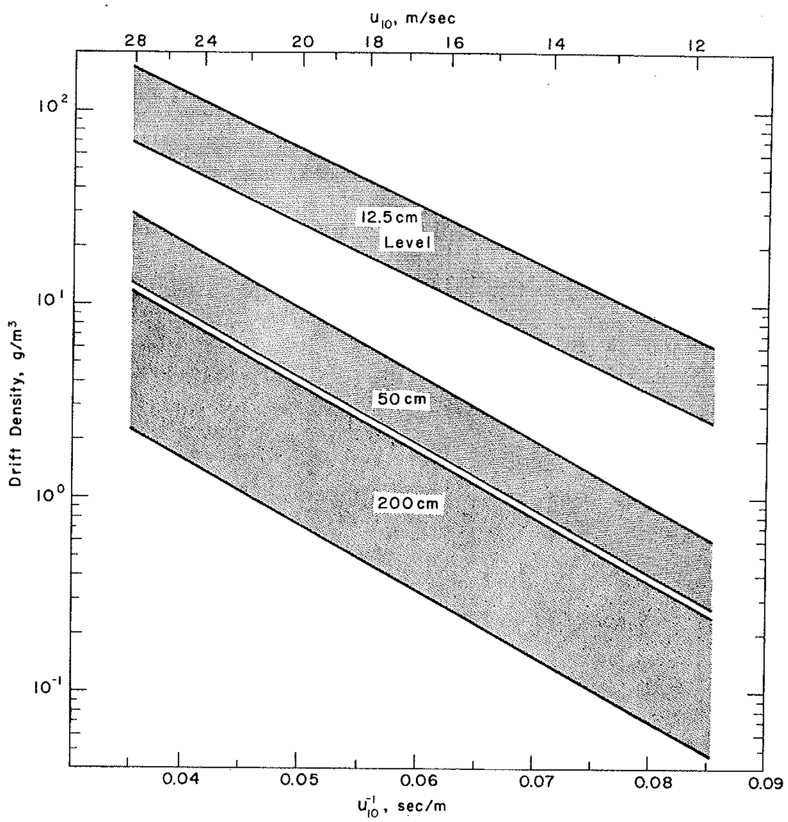

Figure 5. Data bands covering relationships between drift density (concentration) and wind speed at various heights, as observed at 3 different stations (8).

More empirically, there are good linear correlations between log n and log u_{10}, and between log q and log u_{10}, which indicate that, for $z \geq 50$ cm, n is approximately proportional to u_{10}^6 and q is approximately proportional to u_{10}^7. These simple relationships emphasize the very strong dependence of n and q on u.

CONCENTRATION AND FLUX OF FALLING SNOW

When snow is falling in wind-free conditions, the vertical mass flux is given by the accumulation rate at the ground, which is easily measured by exposing a tray of known area for a timed interval and weighing. If mean particle fall velocity is known, mass concentration snow in the air can be found. Concentrations measured by the writer at Hanover, New Hampshire, range from approximately 0.01 to 0.7 g/m^3 as accumulation rate, or vertical flux, ranges from approximately 0.003 to 0.25 g-cm^2/hr.

REDUCTION OF VISIBILITY AND LIGHT TRANSMISSION BY FALLING AND BLOWING SNOW

Particles of falling or blowing snow scatter visible radiation, reducing light transmission and visibility. Detailed measurements by Budd et al. (8), which were in broad agreement with Liljequist's earlier results (24), gave a relation (Fig. 6) between visibility, or visual range, V(m) and snow concentration n (g/m^3).

$$V = 100/n \tag{13}$$

The foregoing figures showing n as a function of z and u can thus be reinterpreted to show V as a function of z and u by appropriate scale changes.

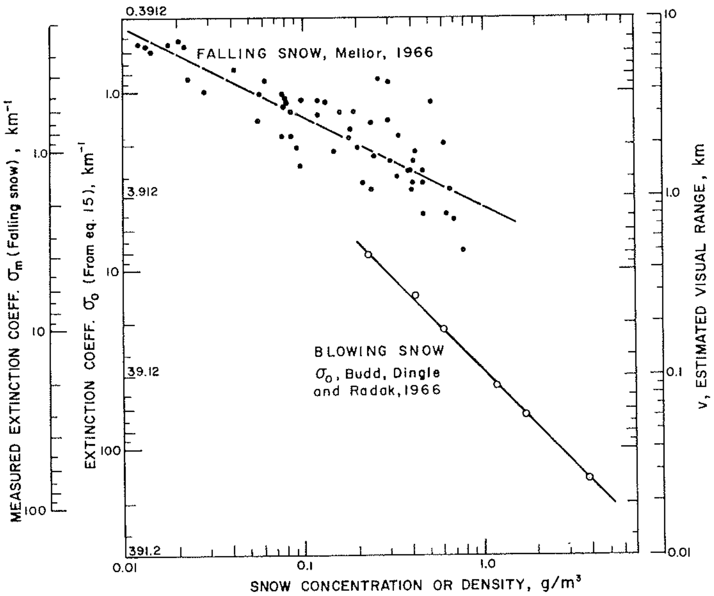

Figure 6. Visual range and extinction coefficient as functions of snow concentration for falling and blowing snow. The left scale gives an extinction coefficient σ_0 calculated on the assumption that liminal contrast is 0.02 and inherent target contrast is -1, and also gives a scale that corrects the data for falling snow in accordance with photometric control measurements.

Mellor (31) measured visibility through falling snow (Fig. 6) and gave an empirical relation between V(m) and snow accumulation rate A(g-cm^2/hr):

$$V = 625\ A^{-0.42} \tag{14}$$

An extinction coefficient σ_O, which gives attenuation rates for transmitted light, can be estimated from visibility data by the relation

$$\sigma_O = 3.91/V \tag{15}$$

More detailed data summaries, together with relevant theory, are given by Mellor (30, 31).

SNOW DEPOSITION ON FLAT SURFACES

A variety of deposition-erosion patterns (ripples, waves, barchans, sastrugi, and dunes) form when snow blows across flat unobstructed terrain. Their general characteristics and dimensions are known, and their modes of formation are understood in broad terms (30), but there is little systematic quantitative information on details of formation. Detailed field research on these features might be valuable because, while they do not significantly affect the wind profile at higher levels during course of formation (8), they are intimately related to wind transport processes and particularly to saltation. Furthermore, because they undoubtedly reflect "wall" structures of the boundary layer, they may well yield information of broad significance.

Deposition-erosion features provide a means of assessing local wind directions and, to some extent, wind strengths. Large whaleback dunes are usually associated with strong winds blowing during major snowstorms, when much new snow is deposited. Ripples, barchans, and sharp-edged sastrugi commonly form when previously deposited snow is being redistributed by "dry" winds. Transverse features (ripples and waves) form in light winds, whereas longitudinal features (dunes and sastrugi) form in strong winds. Some observers have the impression that there is a positive correlation between the wind speed and the height, or length-width ratio, of sastrugi.

FLOW PERTURBATION BY OBSTACLES AND SURFACE IRREGULARITIES

When a wind stream encounters obstacles or surface irregularities, boundary layer separation occurs, turbulent wakes are formed, and preferential deposition and erosion of snow take place. The general proportions and characteristics of eddy zones around typical obstacles are reasonably well known, although there does not appear to be any systematic compilation of such data for a wide range of obstacle types and wind speeds. Deposition and erosion in the vicinity of an obstacle are clearly related to local eddy patterns, and equilibrium, or "saturation," profiles of drifts and scours have been determined for some common obstacles. However, little is known quantitatively about the conditions controlling deposition and erosion, or about the rates at which they occur.

Thus, while flow perturbation by obstacles and irregularities lies at the heart of practical snowdrifting problems, it cannot be treated analytically at the present time. The alternative is to tackle the problem experimentally, either by field observations or by model tests (which might conceivably include analog models).

FIELD OBSERVATIONS ON PROTOTYPES OR LARGE MODELS

Field tests of prototype structures or large models, and field observations on existing structures and features, have provided invaluable information on the drifting characteristics of snow fences, shelter belts, embankments, cuts, buildings, and other structures. Field studies will continue to form an essential part of any balanced research effort (38), but it seems important to distinguish between engineering studies designed to give specific results for local conditions and more fundamental studies designed to provide basic data of broad applicability and control data for model studies.

For basic investigations, ideal test sites are flat, unobstructed areas subject to frequent and consistent occurrence of blowing snow, with a range of wind speeds. Ideally, the sites should be manned continuously. Open plains and frozen lake surfaces are obvious locations for testing, but perhaps the best research sites of all are found on polar snowfields. One advantage of a permanent (polar) snowfield is that tests can run until equilibrium drift profiles are attained, whereas in areas of seasonal snowfall drift accumulation may be terminated artificially. Another advantage of polar snowfields is that the dense snow can easily be formed (and stabilized) to make embankments and cuts. To reap full value from field tests, one should throughly monitor snow transport in the unperturbed flow along the lines developed by Budd et al. (8).

MODELING TECHNIQUES

Direct modeling of snowdrifting may be carried out by using (a) a wind tunnel with introduced solid particles, (b) a wind tunnel without aerosols, and (c) a water flume with introduced solid particles.

Wind Tunnel With Aerosols

Simple wind tunnel experiments using fine powders have yielded useful information on shapes and dimensions of drifts (11, 34, 6, 21). Less empirical experiments designed to provide quantitative information, including rates of deposition, call for more rigorous application of modeling criteria (15, 42, 20, 17, 39, 35, 36, 9). Odar's comprehensive consideration of relevant criteria (35, 36) provides a sound basis for preliminary design of experiments, although some revision in detail may be called for. However, because it is unlikely that all modeling criteria can be satisfied in full simultaneously, judicious selection of the most significant and attainable scaling factors is probably necessary. This selection, together with subsequent evaluation of scaling factors, should be made on the basis of reliable data for the natural phenomenon.

Some wind tunnel tests have been made using ice particles (40), but for most purposes the experimental complications do not appear commensurate with the potential advantages. However, it should be pointed out that snow has adhesion and sintering properties not normally found in many other powders; these characteristics allow snow deposits to form wind-resistant surfaces and to develop shapes (e.g., cornices) that are prohibited for cohesionless powders.

Wind Tunnels Without Aerosols

Use of wind tunnels without aerosols has been proposed as an alternative to direct modeling. Leaving aside simple procedures for defining eddy zones by smoke tracers, quantitative modeling with solid particles involves the following steps:

1. Flow past the structure has to be properly reproduced by satisfying appropriate modeling criteria, which call for geometric and kinematic similarity and scaling of surface roughness;
2. Guided by postulated criteria for deposition or erosion, measurements have to be made on the flow;
3. By using theoretical criteria for deposition, initial deposition rates have to be calculated from the flow measurements; and
4. The base surface of the model has to be reshaped in accordance with results of step 3, and the entire procedure repeated.

Alternatively, it may be possible to establish equilibrium drift profiles by omitting step 3 and warping the model's base surface until flow measurements indicate that stable conditions have been reached (9)

The prime problem is to establish the criteria governing deposition and erosion, and to develop the analytical tools needed for calculation of deposition rates. In early investigations, deposition and erosion in the vicinity of an obstacle were associated with local eddy patterns, and it was assumed that deposition would occur in zones where wind speed was reduced below some critical value. Odar's studies (35, 36) laid emphasis on surface shear stress as a controlling factor, and Cermak (9) made explicit postulations that deposition would occur or cease according to whether surface forces were respectively less or greater than (a) values required for particle motion at the surface or, alternatively, (b) corresponding forces for an unperturbed flat surface away from the obstacle. Cermak's analysis indicated that conditions for initiation of particle movement are given by the dimensionless parameters (u_*/w) and (u_*d/ν), in which d is either particle diameter or equivalent surface roughness and ν is kinematic viscosity of the air. The first of these parameters is of obvious relevance to turbulent diffusion, as it is the inverse of the exponent in Eq. 9. The second parameter is more questionable, because most snow surfaces appear to be aerodynamically rough. A more plausible alternative for the parameter governing threshold shear is one used in essentially similar form by Bagnold (1), Odar (35, 36), Owen (37), and Radok (38): this is the parameter γ discussed and evaluated in the foregoing discussion of saltation. In any event, this topic ought to be reviewed in the light of realistic field data before any modeling is undertaken.

Once the relevant aerodynamic characteristics of the flow around an obstacle have been determined in the particle-free wind tunnel, there remains the problem of computing deposition rate as a function of position. Cermak's notes (9) give no indication how this might be done; they are concerned mainly with delineation of equilibrium drift profiles. Radok (38) argued convincingly that deposition rates ought to be deducible from mass flux divergence considerations; this seems eminently reasonable in the light of turbulent diffusion theory, but practical methods of calculation remain to be developed. In the present state of uncertainty it may be preferable for engineering purposes to approach the problem of deposition rates by considering the energetics, rather than invoking the detailed mechanics, of the process. One possibility would be to determine from wind tunnel tests the power expended by the air stream in drag resistance against an obstacle, and to compare this with the power required to suspend snow particles (given by turbulent diffusion theory) to obtain an estimate of rate of deposition in the vicinity of the obstacle. This would not, of course, give deposition rate as a function of position, but the general geometry of drift patterns could be determined independently from the local eddy structure.

Actually, although modeling without aerosols may have an important part to play in determining aerodynamic characteristics, it does not appear particularly attractive as a final engineering design procedure, as the practical simplification realized by eliminating the aerosol is probably outweighed by additional theoretical uncertainties and practical difficulties in simulating accumulating drift forms.

Water Flumes

Water flumes carrying solid particles in turbulent suspension have been used for modeling as an alternative to wind tunnels, notably by Theakston (43). The fundamental principles governing transport and deposition in a liquid are similar to those involved for wind transport (2, 3, 4, 5), but there are significant differences in magnitude for certain effects, because the densities of liquid and particle are of similar magnitude, whereas the densities of air and typical solids differ by about 3 orders of magnitude. In some respects this makes the problems of liquid transport more difficult than corresponding problems for air transport.

CONCLUSIONS

The basic processes of wind transport are now reasonably well understood, and there is a body of reliable field data for wind transport across flat unobstructed surfaces. The emphasis for fundamental field studies might now be switched to (a) natural deposition and erosion processes on flat unobstructed surfaces, (b) effects of flow perturbation on velocity, mass flux, and particle concentration, and (c) rates of deposition and erosion on surfaces in regions of perturbed flow.

Wind-tunneling modeling procedures in general are highly developed, but so far no fully satisfactory techniques for modeling windblown snow have appeared. This situation can probably be remedied by drawing on reliable field data for a review of modeling criteria and establishment of suitable scaling factors. Modeling with introduced aerosols is immediately feasible, and it ought to be possible to establish both deposition patterns and rates of deposition. Modeling without aerosols is more uncertain; it is immediately capable of giving potential deposition zones, but prediction of deposition rates depends on untested hypotheses. More field data and improved theory for perturbed flows seem to be a prerequisite for complete modeling without aerosols.

In the practical field of engineering control the immediate outlook is for "more of the same," but over the longer term there ought to be scope for more efficient application of control principles by exploiting better education and communication, and by routine application of modeling. Needed to achieve the goal of prompt and inexpensive model tests are a special wind tunnel and trained staff capable of serving engineers throughout the country on a reimbursable basis.

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Informal Discussion

A. R. Jumikis

There are arguments pro and con. There are no cookbook recipes available for all road and snowdrifting conditions.

L. Gary Byrd

Perhaps there is a warrant for research in the economic area relative to this whole question of the investment in achieving drift control.

M. E. Volz

I was recently subjected to a practical application of the nonpermeable snow fence that is made out of snow, and it worked very successfully. It was at the airport at Madison, Wisconsin. On the upwind side of the runway, which is the prevailing cause of their snowdrifting, they had plowed back about 20 or 30 ft and made a small ridge so that they did not have a problem close to the runway. They then proceeded out onto the field approximately 200 ft and very slowly raised a huge windrow. It was the most successful thing that I have seen and did not cost anything beyond the mechanics of actually building this nonpermeable snow fence.

Jumikis

That is true. If one has the manpower, one can make a good dense snow fence or a snow wall by means of blocks of snow or simply by shoveling up a snow wall. This method has been used in Russia. However, this method cannot be used with the first drifting snow in winter because not enough snow is yet available for building a snow fence.

L. H. Watkins

I should like to make an observation about a rather contradictory sort of problem that arises with us because we are pressed very often to put fences alongside highways for a number of different reasons, not only as snow fences but also as noise barriers and windbreaks. For the last 2 purposes, we erect the fence as close to the carriageway as we can get it and then it is in the optimum position for depositing snow on the carriageway when the snow falls. I do not really know the answer to this one. If you can design a barrier that will do all these things, I would be very much obliged.

Aerodynamic Snow Fences to Control Snowdrifting on Roads

Alfreds R. Jumikis

This paper describes some problems of snowdrifting control on roads in open terrain. Some of the relationships between geomorphological-climatic factors and snow fences as snowdrifting control devices are discussed. The aerodynamic-snow mechanics aspects of snow fences and flow processes of air-snow currents across dense and permeable snow fences are described, rough calculations are made for spacing of snow fences, and difficulties in theoretical analyses of aerodynamic snow fences are discussed. The paper also suggests additional studies that are needed to improve the effectiveness of snow fences. These include studies of geomorphology and climate of regions prone to snowdrifting, aerodynamics of snowdrifting, and aerodynamic-snow mechanics of various kinds of snow fences and their components.

Clearing and protecting streets, highways, and airfield runways, taxiways, and service roads from snow are undisputed necessities for unimpeded, year-round operation of transportation on the ground, especially during, and even for some time after, snowstorms.

Discussion of snow removal practices on roads is beyond the scope of this paper. Snow removal by mechanical means has been adequately discussed by others (1, 2, 3). This paper only discusses the protection of roads against snowdrifts, viz., snowdrift control in open terrain. Some of this discussion pertaining to snowdrifts on roads may also be applicable to winter maintenance of airfield runways.

SNOWDRIFTS

During snow periods with heavy winds there is a tendency for the snow to drift. Frequently snowdrifts on roads bring vehicular transportation to a complete standstill. The magnitude of snowdrifts depends, among other things, on the quantity and nature of snow and the velocity of the wind. The wind may pick up snowflakes from a snow blanket on a field adjacent to a road. It is known from fluid mechanics that the velocity of the air current, viz., snow-laden wind, is reduced by an obstacle in the way of the wind. Any obstacle that brings about a reduction in the velocity of the air current carrying snow will cause some of the snow to be deposited in a heap, commonly known as a drift. Such obstacles may be grass, brush, shrubs, trees, fences of all kinds and built-up areas, variation in the relief of the terrain on both sides of the road, embankments, fills, cuts, position of the road, roadside snowbanks created by snowplowing, and many other physical obstacles. Thus, under certain combinations of meteorology, aerodynamics and physical terrain, such as wind obstacles along the road, decrease the velocity of the wind blowing across the road enough to cause snow to accumulate and to pile up on the roadway. This affects the traffic on the road adversely, or may even render the road impassable. Therefore, prevention by control of drifting snow or, rather, reduction of the perils of snowdrifts so far as is physically possible and economically feasible involves a judicious introduction of drift control devices to reduce the wind velocity at or near the roads and runways.

REMEDIAL MEASURES FOR SNOWDRIFT CONTROL

Some of the common remedial measures used to control drifting and accumulation of snow on roads are removal of objectionable obstacles (fences, trees) that may cause snowdrifts; planting of rows of trees to serve as wind barriers; planting of areas of trees to serve as snow accumulation "reservoirs"; proper road and alignment design in drift-prone areas; and erection of artificial snow fences. Experimental studies of wind-breaking and snowdrift control by tree-planting have been performed and described by Finney (4).

Each of these remedial measures has its advantages and disadvantages. For example, the "natural" snow fence fits in very nicely with the timely trend toward improvement and beautification of the roadside and highway appearance. Effective as it may be in drift prevention, the natural fence, however, also has its inherent disadvantages:

1. It may require a wide right-of-way;
2. It is relatively expensive in respect to planting, growing, and maintenance;
3. It takes many years (about 6 to 8) to grow a hedge and about 15 years to grow some species of trees; and
4. Once planted, it is impossible to shift and erect the natural fence against the changing direction of the winds.

Artificial snow fences as snowdrifting control devices have proved to be a practical, effective, and relatively inexpensive means both here and abroad for reducing the wind velocity and thus protecting roads and railroads from snowdrifts.

The principle involved in using snow fences is their proper erection at some distance away from the road on its leeward side. In front of the windward side and behind the fence (on the leeward side), snowdrifts are formed where snow is deposited and stored before it can reach the road. The proper distance from the pavement edge to the snow fence varies from approximately 75 to 100 ft. The actual distance must be determined in accordance with local conditions, of course. From practical experience this distance is an empirical function of the height of the fence. For example, in some regions, by method of trial and adjustment, snow fences are placed from 6 to 15 to 20 times the height of the fence from the point where snowdrifting is to be avoided, viz., from the edge of the pavement. Fences are placed parallel, perpendicular, or at an angle to the road, depending on the direction of the prevailing wind.

FACTORS INVOLVED IN PLACING OF SNOW FENCES

As simple as the problem of placing the snow fence might appear superficially, in reality it is not that easy. The position of the snow fence involves not merely its height, but also meteorological and hydrological conditions of the locality such as fluid mechanics of the snow-laden air current; aerodynamics of the snow fence; physical properties of the air, snow, and the fence itself; snow mechanics (5); the theory of snowdrifting (6); and effective drainage facilities for removing snow meltwater as quickly as possible during thawing periods (the road must be "dry" even in wet weather). It is also essential that the drainage be kept warm to prevent freezing; geomorphology of the terrain, topography, and possibly some other factors must be considered. Continuous study of weather trends would disclose the regimen and "detours" of the prevailing winds and snowstorm paths. The properties of snow of interest are density, specific gravity and hardness, temperature and moisture content, cohesion, plasticity, viscosity, and shear strength. Thus snow mechanics is of interest not only in avalanche studies, forestry, military operations, snow sports, and snow densification but also in snowdrifting control and research.

From this short review it may now become apparent at once that the problem of placing the snow fence for proper functioning and the theory on which proper functioning of such a fence is based are anything but scientifically simple. This problem is tricky to solve satisfactorily. It may be said at this point that this is one of the examples where winter service road maintenance men intuitively and correctly recognized very early and utilized with reasonably practical success the snow fence as a snowdrifting control device before science and engineering were able to supply the logic. All these factors call for an experimental study for the development of an aerodynamic snow fence as an effective snowdrifting control device.

KINDS OF SNOW FENCES

The kinds of snow fences used by the various highway departments are described in their highway maintenance manuals, in the Highway Engineering Handbook (7), and elsewhere (2, 8, 9, 10). Paper snow fences have been used successfully in Michigan (8, 9). However, in this discussion, all snow fences are classed as solid or impervious to snow, and open or pervious to snow.

If a snow fence contains horizontal or vertical gaps (voids) or "pores" between adjacent boards, pickets, or paper stripes, the snow fence is open, or permeable to snow. The perviousness of a snow fence may be characterized by its "void ratio" or by its "density ratio." The void ratio is a number that shows the proportion of void (open gaps) to solid areas in the frontal portion of the material or obstacles. Density ratio is the ratio of the frontal area of the snow fence material to the total frontal area of the fence (including open gaps).

THE FUNCTIONING OF A SOLID, IMPERMEABLE FENCE

The fundamentals of the theory of snowdrifting have been dealt with by Dyunin (6) and others. Unfortunately, there has been very little technical explanation of the functioning of both solid and permeable snow fences. The approach followed so far in the development of methods of snowdrifting control has been empirical. The theoretical aspects of this problem have received very little attention in the past. It is for this reason that research on aerodynamic snow fences is suggested here.

The following is an approximate description of the functioning of snow fences, based on observation.

When a fluid such as a horizontal, snow-laden air current meets and flows about an obstacle perpendicular to the flow such as a dense, impermeable snow fence, it tends to flow around the top of the fence. The velocities of the current on either side of the fence have different magnitudes. The streamline pattern of the air current normal to the blunt, impermeable snow fence is shown in Figure 1. On the windward side of the fence the velocity of the current, v_W, is greater than that on the leeward side, v_L.

Aerodynamic studies indicate that upon flowing around the sharp edge of the upper end of the vertical plate (fence) a separation of the streamline pattern takes place; the snow-laden air current is torn off and deflected, and whirls or eddies of the air-snow mixture set in on both sides of the dense fence, hurling and whirling along the dead,

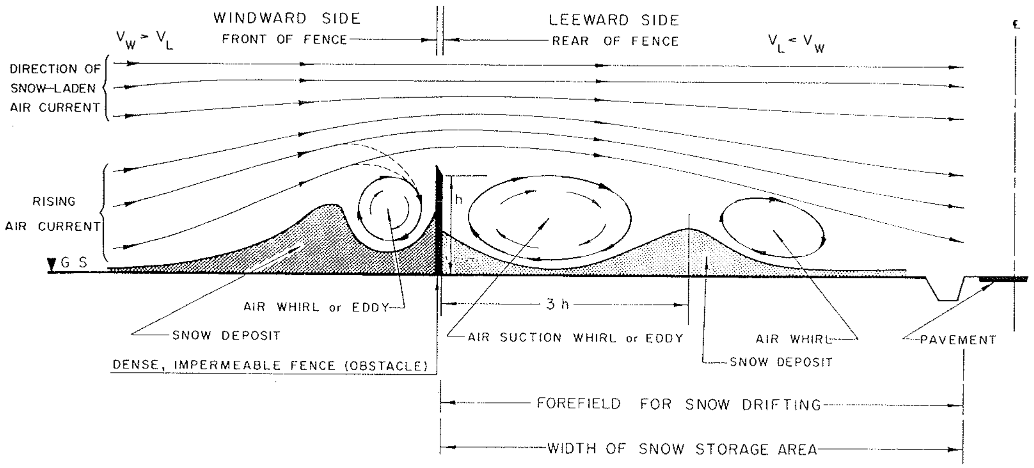

Figure 1. Snowdrifting at an obstacle—initial phase of performance of a dense snow fence, and snow accumulation in wind-calm zones.

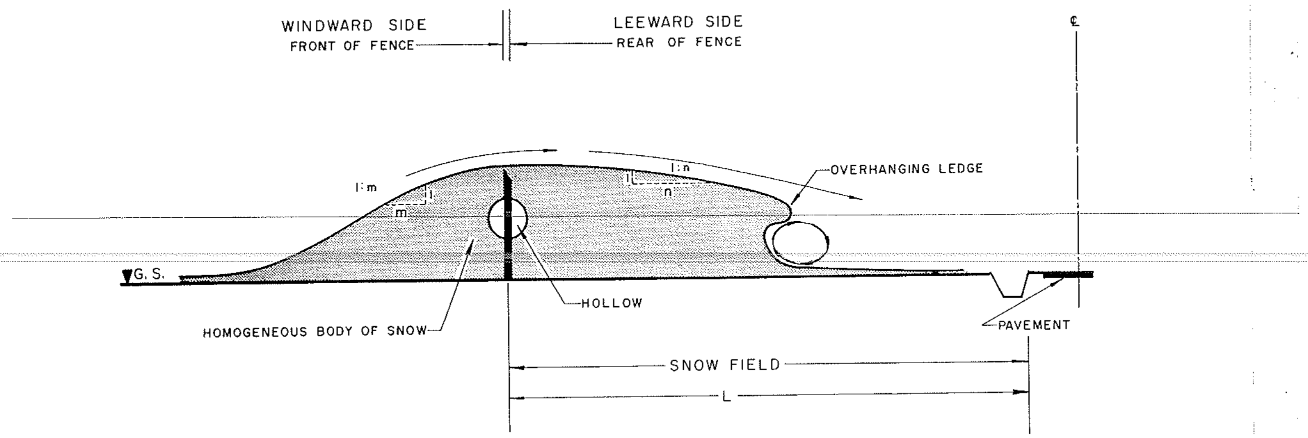

Figure 2. Final phase of performance of a dense snow fence.

deposited snow. Large drag forces develop there, eddying and carrying away the loose masses of snow (dissipation of energy of the air-snow fluid). When the momentum of the eddies becomes large enough, the eddies break away, allowing another to form, and this process repeats itself.

In the wake (leeward side) of the air-snow current behind the obstacle, the local pressure is greatly reduced. With the decrease in velocity of the air-snow current here and because of the eddying (reduced pressure and suction whirl shown in Figure 1), the snow falls out from the air current and deposits in the relatively calm forefield (snow field) or snow storage area. The heavy snow flakes fall out first.

If the forefield is wide enough, the air current is relatively free of snow when it sweeps across the road. Thus the drifting spends itself and becomes less and less severe as it peters out. Among the properties of snow it appears that viscosity of the air-snow mixture is the root of the drag problem in snowdrifting. The snowdrifting process continues for as long as the snow fence is effective in reducing the velocity of the wind.

The picking up, the transport of snow flakes by the air current, and the formation of snowdrifts begin on the average at a wind velocity from 4.5 to 8.0 m/sec.[5] The average unit weight of a loose, powdery snow at calm varies from 60 to 100 kg/m^3[5]. A denser, wind-deposited snow, depending on its moisture content, may have a unit weight from 250 to 370 kg/m^3[11].

Observations made of air-flow currents indicate that the bulk of the snow mass is carried by the lower part of the wind current. The densest air-snow current is approximately 2 m above the ground surface, and about 90 percent of the snow is carried within the lower tens of centimeters, and about 80 percent within the lower 4 centimeters. This explains why no high snow fences are in use. The height of snow fences is usually from 1.5 to 2 m (about 4 to 6 ft).

When the drift is built up to the top of the fence, it is said that the fence is filled or saturated (Fig. 2). A dense snow fence produces especially strong suction and thus short, thick drifts. But the consequence of this is that such a fence soon becomes saturated and thus ineffective. Because of this disadvantage, dense snow fences have seldom been used so far.

THE FUNCTION OF A PERMEABLE FENCE

If a snow fence has voids or gaps, its aerodynamics is more complex than that of a dense fence. The performance of a horizontally pervious fence in its initial phase is shown in Figure 3. The dotted line indicates the final phase of the performance of the snow fence when filled. The principal advantages of a pervious snow fence over a dense

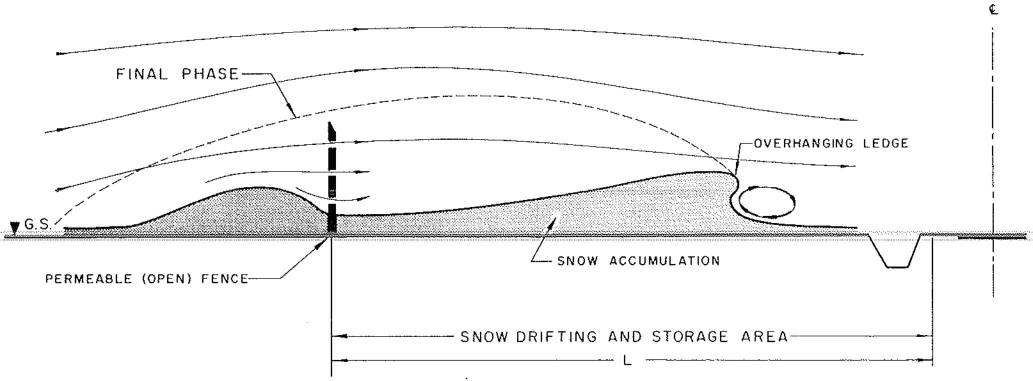

Figure 3. Performance of a horizontally pervious snow fence.

one are less material, light weight, and much greater width of snow drifting and eddying area, the snow storage area between the pervious fence and the road. Also, here the volume of the accumulated snow is greater than that around a dense fence. The effectiveness of the permeable snow fence depends on the void ratio, of course.

From this discussion one already should have gathered that the functional intent of a snow fence is not the prevention of drifting of snow. On the contrary, the function of the snow fence is to facilitate purposive drifting and deposition of snow in an area away from the roadway, i.e., in the area between the fence and the highway. Hence, the term "control of snowdrifting" is used. The real purpose of the snow fence is thus to reduce the velocity of the snow-laden air current, thus facilitating the fall-out and achieving the wind stream and the deposition of the snow before it is carried to the road. Such a function of the fence is continuous for as long as the fence remains effective in reducing the velocity of the wind or air current.

SNOWDRIFTING ON FILLS AND IN CUTS

The width of the snow storage area at a fill or cut of a road also depends on the steepness of the fill. At steep slopes, 1:1 to 1:2, the snow is swept across the road and, depending on the character of the wind and snow, is deposited partly on the pavement, partly on the shoulder, and partly on the leeward slope of the road. This also requires an effective drainage system to carry away the meltwater of snow quickly. With gentler slopes of low fills (less obstruction) from about 1:3 to 1:4 or flatter, the wind should carry the snow up the slope and across the pavement and deposit it on the leeward side of the slope (1). The trend in cross-sectional design concerning snowdrifting is toward the use of 1:5 slopes. Flattened slopes and the rounding of slope junctions facilitate the flow of the air-snow current; thus the deposition of the snow is controlled to some extent. Also, gentle slopes render a more stable fill than those with steeper slopes. Up to now, the rounding of slope junctions has not been practiced widely enough.

Because the streamlines of the wind (air-snow current) over the road on a low fill are squeezed closer together, there results an increased wind velocity across the pavement. Therefore, the snow is swept across and away and deposited next to the road on its windward side.

As to the cuts, during severe snowstorms, there forms in deep cuts a perfect, closed whirl-drum of air-snow mixture (Fig. 4). With a ratio of width, W, of cut at its top to depth, D, of less than 4:1 $[(W:D)<(4:1)]$ and at a wind velocity intensive enough, the eddying motion carries the snow out from the cut in such a way as to free it of drifted snow. A ratio larger than 4:1 may result in partial or complete drift in the cut.

Hence, from the viewpoint of aerodynamics, height of fill, curved slopes of fills and cuts, and depth of a cut would have an effect on the drifting regimen of snow.

Sometimes heavy drifts on roads are formed as a result of maintenance operations such as snow removal. For example, the first, thin cover of snow on the pavement may

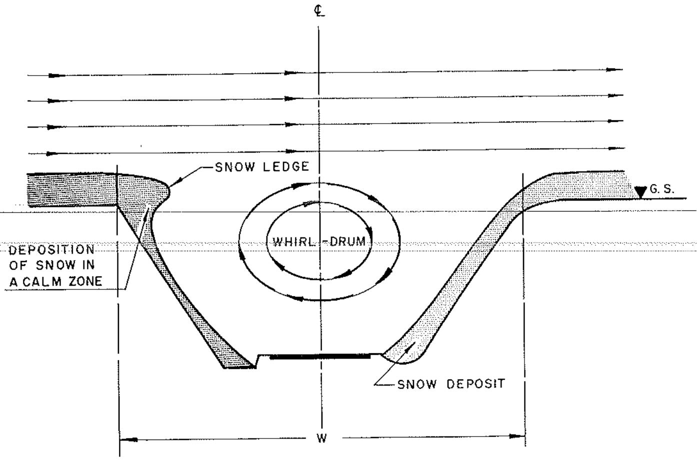

Figure 4. Perfect whirl-drum in a cut.

become riffled ("washboarded") by traffic or from plow lines. These act as snow retardants and accumulators. After snowdrifting has begun, the drifts on the pavement increase rapidly.

VOLUMETRY OF SNOW FENCE DRIFTS

The slopes of the volume of the accumulated snow on both sides of the saturated snow fence may be used for practical purposes in calculating approximately the necessary height, h, of the snow fence as a function of the vertical cross-sectional area, A_S. For example, assume that there is a saturated snow fence-terrain system as shown in Figures 5 and 6. The calculations are as set forth in examples 1 and 2 that follow.

Example 1

The snow fence is set back from top edge of slope (Fig. 5). The total cross-sectional area A_S of accumulated snow is

$$A_S \approx \Delta BC + \Delta ABC + \Delta DEF \tag{1}$$

or

$$A_S \approx (0.5)(8h)(h) + (0.5)(10h)(h) + (0.5)(1.5)(d^2) = (0.5)[(18)h^2 + (1.5)d^2] \tag{2}$$

The height of the snow fence is

$$h = \frac{1}{6}\sqrt{4A_S - 3d^2} \tag{3}$$

The position of the snow fence must be at a distance L = (10)(h) - (1.5)(d) from the edge F of the cut.

$$L = (10)(h) - (1.5)(d) = \frac{10}{6}\sqrt{4A_S - 3d^2} - (1.5)(d^2)$$

$$= \left(\frac{1}{2}\right)\left[\left(\frac{5}{3}\right)\sqrt{4A_S - 3d^2} - (3)(d^2)\right] \tag{4}$$

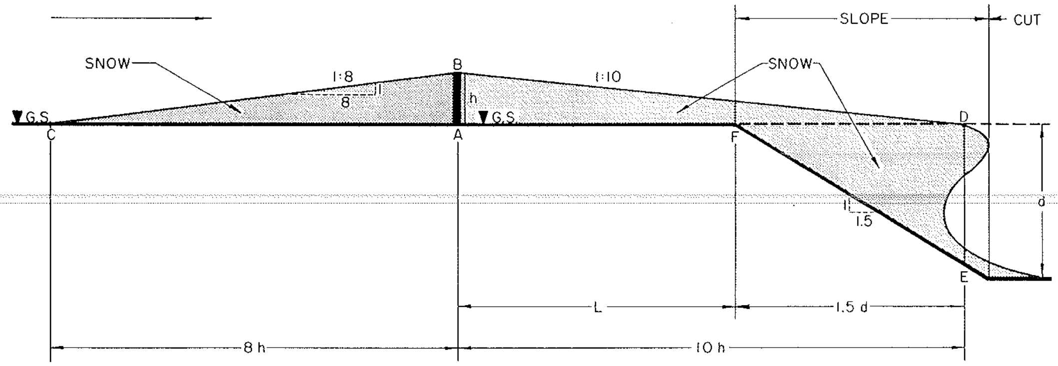

Figure 5. Saturated snow fence-terrain system with fence set back from top edge of cut.

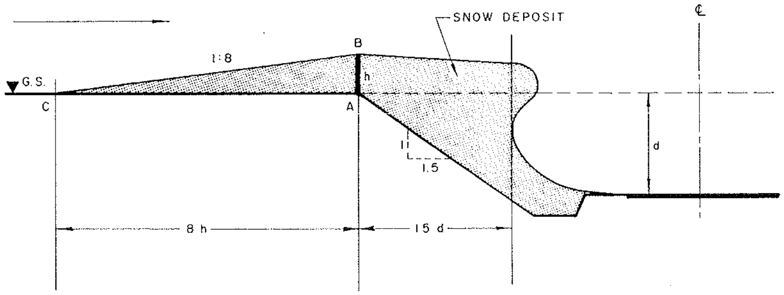

Figure 6. Saturated snow fence-terrain system with fence at top edge of cut.

The specialization of Eqs. 2 and 3 is as follows:

1. When there is no cut, then d = 0 (level terrain), and the needed height of the snow fence is

$$h = \frac{1}{3} \sqrt{A_S} \tag{5}$$

Also, the width of the snowdrift storage area, L, on the leeward side of the fence for such a case, is

$$L = (10)(h) = \frac{10}{3} \sqrt{A_S} \tag{6}$$

2. When there is no snow fence used, then the allowable depth, d, of the cut free of danger of the drifting of snow is calculated by Eq. 2 as

$$d = 2\sqrt{\frac{A_S}{3}} \tag{7}$$

i.e., at such a depth, d, no snow fence is needed.

Example 2

The snow fence is at the top edge of the slope (Fig. 6). The total cross-sectional area of accumulated snow is

$$A_s \approx (0.5)(8h)(h) + (0.5)(1.5d)(d) + (1.5)(d)(h)$$
$$= (0.5)(8)(h^2) + (0.5)(1.5)(d^2) + (3/2)(h)(d) \quad (8)$$

The height of snow fence is

$$h = \frac{3d}{16} \pm \frac{1}{16}\sqrt{64A_s - 39d^2} \quad (9)$$

The specialization of Eq. 9 is as follows:

1. When d = 0 (no cut), then

$$h = +\frac{1}{2}\sqrt{A_s} \quad (10)$$

2. When h = 0 (no fence), then

$$d = \frac{4}{3}\sqrt{A_s} \quad (11)$$

i.e., at such a depth of cut, no snow fence is needed.

SNOW FENCE AND DRIFTING CONTROL STUDIES

Because in a particular environment each kind of snow fence performs differently, it is here suggested that scientific studies of their effective functioning should be pursued along the following lines: the geomorphologic-climatic aspect; the aerodynamics of snowdrifting; and the aerodynamic-snow mechanics aspect of the function of various kinds of snow fences and their components.

THE GEOMORPHOLOGIC-CLIMATIC ASPECT

Snowdrifting on a road is decisively influenced by the form of the geomorphology of the terrain, hydrology, and climatic conditions during winter in the region concerned. Therefore, to perform a thorough investigation along these lines and to plan snowdrifting control facilities, one must learn and know the causal connections between the various elements in question. These studies include the following:

1. The relationship between the land form (geomorphology) and the prevailing wind regimen (intensity, direction, duration, wind gaps, and wind jets) should be understood.
2. Hills, valleys, ridges, depressions in the ground surface, woods, fills and cuts, snow banks, as well as open spaces affect the wind regimen and hence the regimen and control of drifting of snow. These obstacles cause a change in the angle of direction of the wind thus changing the snowdrifting regimen. For example, fills up to about 9 m in height may cause a reduced velocity of the air-snow current across the roadway thus bringing about snowdrifts on the pavement.
3. Highway fills or cuts may change the wind and snowdrifting regimens as compared with those prior to such construction.
4. Possible danger to soil erosion and frost action problems in soil because of melting snow along the highway must be considered prior to road construction.
5. Frozen soil may be the cause of a 100 percent runoff. This may tax the drainage facilities and cause flooding of roads and runways.
6. Part of the study of the climatic conditions should include wind profile measurements. Such data may help also in laboratory research using terrain-road models.
7. A snowdrifting warning service should also be investigated.

These and other multiple climatic factors and their resulting phenomena also bring to the fore the question whether wind (snow) protection of roads is always advisable. Under certain conditions such protection may turn out to be disadvantages or even dangerous to motorized traffic.

However, whatever the situation, the highway alignment must fit in properly geomorphologically, hydrologically, and climatically with the terrain in respect to drainage conditions, wind regimen, and aesthetic appearance of the road-terrain system. Also, the road should lie beyond the leeward limit of the drifting area of snow.

THE AERODYNAMIC-SNOW MECHANICS ASPECT OF A SNOW FENCE

The functioning of snow fences depends on their physical and aerodynamic properties and on those of the wind. In other words, the snowdrifting control depends on the shape of the fence contour, i.e., height and density of the fence; size and smoothness or roughness of the surface and edges of the pickets; drag coefficient of the fence and its components; nature of the gaps; density, viscosity, elasticity, and temperature of the compound fluid air-snow; and the fundamental properties of streamline separation.

The aerodynamic prototype of a dense fence is the fluid flow around the top of a vertical, flat rectangular plate of small height. Here the flat plate is the simplest possible aerofoil section. On a blunt object the boundary layer (contour of the dense fence) of the air-snow current causes the streamlined flow to separate from the leading edge of the fence and thus causes a reduction in velocity of flow, decrease in pressure behind the point of separation, and eddies. The phenomenon of separation becomes a very important factor in determining the characteristics of the fluid flow about the snow fence, calling for a study of the mechanism and fundamental properties of the separation. The results of such a study depend critically on the assumptions of potential streaming and whether the surface of the fence is smooth or rough, and whether the leading edge is blunt, sharp, or rounded.

The analytical studies become even more difficult with permeable fences. The flow past the individual vertical pickets and/or horizontal boards and paper ribbons, the separation of flow at the top of the fence and along the contours of the gaps, and the mutual influence from the adjacent pickets or gaps in the fence bring about a very involved streamline pattern, flow separation, and consequently a very complex eddy regimen. All these phenomena present great computational difficulties for a single, solid, vertical plate, and even greater difficulties for a permeable snow fence.

Because the snow fence problem does not lend itself to a satisfactory analytical treatment, it is suggested that aerodynamic snow fence studies should be performed experimentally in the laboratory as well as in the field, along with geomorphological and climatic studies of the region in the context of effective snowdrifting control on roads and airfields.

SUMMARY

1. The theoretical aspects of methods of control of snowdrifting have received very little attention in the past.
2. The phenomenon of snowdrifting is curbed by the erection of snow fences along roads for the purpose of controlling snowdrifting on them.
3. Snow fences are helpful, but where the country is hilly they are not always effective.
4. A discussion of the function of dense and permeable snow fences is given in this paper.
5. The need for knowing the geomorphological and "wind climate" factors in conjunction with snowdrifting control by means of snow fences is here brought to the fore.
6. Snowdrifting control systems must be designed and adjusted to local snow conditions.
7. The performance and effectiveness of snow fences can be learned from the following scientific and experimental studies: geomorphologic-climatic conditions; aerodynamics of snowdrifting; and aerodynamic-snow mechanics of various kinds of snow fences and their components.
8. The highway alignment must fit properly geomorphologically and climatically in the terrain with respect to drainage, snowdrifting control, and aesthetic appearance.

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Locating Snow Fences in Mountainous Terrain

R. A. Schmidt, Jr.

A series of tests with large snow fences to control snow accumulation in alpine areas of central Colorado has provided greater understanding of the effects of surrounding terrain on snowdrift control with fences. Cross-sectional profiles of the resulting snowdrifts show that an upslope approach to the fence causes a short, high drift to form compared to the long shallow drift formed with a downslope approach. In the downslope approach, however, the total volume of snow trapped by the fence may equal or exceed the volume in the drift behind a fence with an upslope approach. Problems of locating fences for maximum effectiveness in irregular terrain are complicated by the need to maintain a gap between the fence and ground throughout the snow season. Placing fences in the lee of a ridge crest or other natural terrain break often increases the adverse pressure gradient and results in snow deposition upwind of the fence. Some criteria for avoiding this situation are presented.

Snow deposition in irregular terrain can be viewed as the interaction of 2 mechanisms: (a) transport of snow by wind and (b) airflow over natural terrain. These 2 mechanisms are examined briefly to develop a general idea of how they interact to cause snow deposition. Although knowledge of either mechanism is presently far from satisfactory for quantitative predictions of snow deposition, the general concept is used to explain snowdrift configurations behind fences in several terrain situations.

Throughout the paper, flow is considered turbulent and two-dimensional, with neutral atmospheric stability. Although this is far from a realistic model for the overall problem, it provides a point of departure and in some situations perhaps meaningful results.

SNOW TRANSPORT BY WIND

A summary of the state of knowledge concerning snow transport was presented by Mellor (1) and more briefly by Radok (2). Data presented by Budd et al. (3) and the analysis by Budd (4) seem to provide a satisfactory expression for the relative snow concentration profile over horizontal terrain. For a given particle size, this relationship states that the logarithm of drift density is proportional to the logarithm of height. The proportionality is determined by the shear stress. As shear stress increases, drift density at a given level increases. In deriving this relation, shear stress was assumed constant with height.

The snow concentration profile is linked to the wind velocity profile by assuming that the exchange coefficient for snow is equal to the turbulent eddy viscosity. For a constant shear stress through the layer of flow, the eddy viscosity and therefore the exchange coefficient for snow increase in direct proportion to height. The results reported by Budd et al. (3) justify these assumptions, at least for a first approximation over a horizontal surface.

The analysis for a horizontal surface provides a framework for investigating snow transport over irregular terrain. Radok (2) argues that deposition or erosion at a snow surface should be reflected by changes in the mass flux of drift snow. Thus, changes in the snow concentration profile in the direction of flow should be balanced by net accumulation or erosion. These changes in the vertical distribution of drift snow should correspond to variations in the turbulent shear stress distribution and mean wind velocity profiles. This leads to the question, What is known of the mean wind velocity profiles and the turbulent shear stress distribution over topographic obstacles?

WIND OVER NATURAL TERRAIN

Like that of the mechanism of snow transport by wind, knowledge of airflow over natural terrain is more extensive for horizontal surfaces. In such cases, the pressure gradient in the direction of flow is assumed to be zero for the layer near the surface, and shear stress is taken as constant and equal to the surface shear stress. These assumptions lead to the logarithmic mean velocity profile, which describes measurements in this layer quite well for neutral atmospheric stability.

As air moves over irregular terrain, local pressure gradients develop in the direction of flow. Near the windward surface of a hill or ridge, for example, flow moves along a favorable pressure gradient; that is, the pressure decreases in the direction of flow. Air moving leeward from the crest of a hill or ridge does work against an adverse pressure gradient where the pressure increases in the direction of flow. Work is done by wind against an adverse pressure gradient at the expense of flow momentum near the surface. If this momentum loss is sufficient to reduce mean velocity near the boundary to zero, the flow separates. It is primarily momentum considerations that lead one to examine the local pressure gradients.

To see what changes these local pressure gradients might cause in the mean velocity profiles and turbulent shear stress distribution, one must look to laboratory experiments on airflow with pressure gradients. Only a few wind profiles have been measured near the surface of irregular terrain, and there are no data for the turbulent shear stress profile above such a boundary.

Studies on the development of a turbulent boundary layer with pressure gradients in the direction of flow have many practical applications in the design of aerofoils, diffusors, and other devices. Much of this work is summarized by Schlichting (5). Several more recent studies also provide measurements of the turbulent boundary layer developing in one or more pressure gradients (6, 7, 8).

Detailed pressure gradient data for atmospheric flow over a terrain obstacle are not available to compare with a particular set of wind tunnel measurements. The general pattern of mean velocity profiles and the shear stress distributions for favorable and adverse pressure gradients are shown in Figures 1 and 2. These diagrams are designed to show the general relationships from a number of laboratory experiments and are not based on a particular set of measurements. For a favorable pressure gradient, flow accelerates and the mean velocities increase in the direction of flow (Fig. 1). This corresponds to a maximum shear stress at the surface and increasing shear stress in the direction of flow. The mean velocity profiles in an adverse pressure gradient (Fig. 2) show a decrease in velocity along the flow, with the largest deficits near the surface. The general features of the shear stress distributions shown in Figure 2 are (a) a

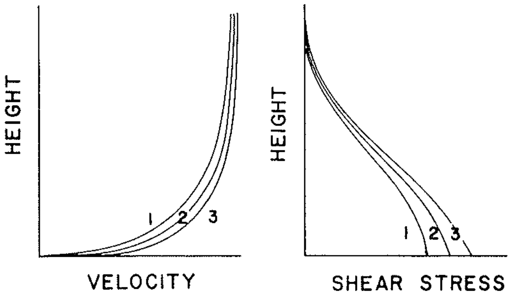

Figure 1. Generalized pattern of mean velocity profiles and shear stress distribution in a favorable pressure gradient (numbers indicate increasing distance downstream).

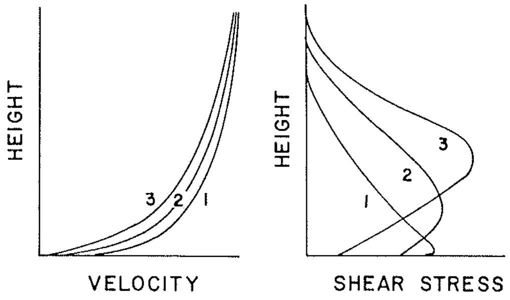

Figure 2. Generalized pattern of mean velocity profiles and shear stress distribution in an adverse pressure gradient (numbers indicate increasing distance downstream).

decrease in surface shear stress in the flow direction and (b) a maximum in the shear stress distribution that moves away from the surface as flow moves downstream.

To summarize: (a) For a given particle size distribution, the relative concentration of snowdrift depends on the vertical distribution of wind shear; (b) local pressure gradients developed by air flowing over irregular terrain result in changes in the vertical distribution of wind shear; (c) for favorable pressure gradients, the maximum shear stress occurs at the surface, and the surface shear stress increases along the flow; and (d) adverse pressure gradients result in decreasing surface shear stress along the flow, and a maximum shear above the surface. If the gradient is strong enough, flow separates from the surface.

For example, consider a two-dimensional turbulent flow across a snow-covered ridge. From experience, erosion is expected on the windward ridge face, with deposition of snow on the leeward slope. These 2 situations should be reflected by the snow concentration profiles. On the windward slope, with a favorable pressure gradient, the shear stress is largest at the surface. Therefore, the snow particle concentration should be larger near the surface than for the horizontal case. Because shear stress increases along the flow, drift concentration should increase as flow moves toward the crest. As flow moves into the adverse pressure region lee of the crest, surface shear stress decreases and some of the snow load in the lowest layers should return to the surface. At the same time, the concentration at higher levels may be increased by the developing shear stress maximum. This should give a profile with lower relative snow concentration near the surface, and a net decrease in mass transport.

An interesting point based on this argument is that deposition should begin before the flow separates. Snow may be deposited on the lee slope without flow separation. In this case the adverse pressure gradient is strong enough to retard flow near the surface. This decreases the shear stress and thus the snow concentration, but it does so gradually enough so that flow does not separate. At the other extreme, a strong adverse pressure gradient that results in separation may develop an eddy with reverse flow strong enough to transport snow up the lee slope. Much of the work on snow deposition, including the wind tunnel studies by Finney (9), is based on the assumption that the snowdrifts tend to fill the eddy zone. The successful application of these studies justifies this assumption for many situations. There are cases, however, where the arguments presented earlier must be considered, as the next section shows.

SNOW FENCES ON MOUNTAINS

The general concept developed earlier is used here to explain the effects of snow fences in several terrain situations. A snow fence represents an obstacle to the natural airflow that produces additional local pressure gradients. In each case presented, the adverse pressure gradient downwind of the fence is considered as an addition to the pressure gradient associated with the terrain configuration. The resulting drifts are examined from the standpoint of (a) total drift accumulation and (b) maximum drift length, 2 characteristics of major interest in snowdrift control.

Case 1—A Snow Fence on a Uniform Windward Slope

The adverse pressure gradient associated with the fence is added to the favorable pressure gradient created by flow up the windward slope. The effect of the fence is reduced by the terrain gradient. Both the total drift accumulation and the maximum drift length should be less than expected for the horizontal situation. Figure 3 shows that this is the case for the maximum drift length.

Case 2—A Snow Fence on a Uniform Leeward Slope

Here the adverse pressure gradient produced by the fence is added to the natural adverse pressure gradient. A larger fence effect should result in increased drift accumulation and maximum length compared to the horizontal case (Fig. 3). For example, a fence 4 m high with 1-m gap was located upwind of a depression in a long lee slope on Mt. Evans in Colorado. The resulting drift had a maximum length on the order of 30 times the fence height with a fairly uniform increase in depth (Fig. 4a).

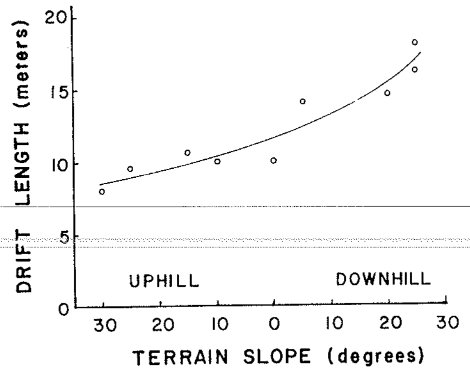

Figure 3. Maximum drift length as a function of terrain slope (10, Fig. 83).

One problem that arises from locating a fence in a natural adverse pressure region is that the fence becomes buried in the drift. This results in expensive maintenance unless the fence is designed to withstand the snow settlement load.

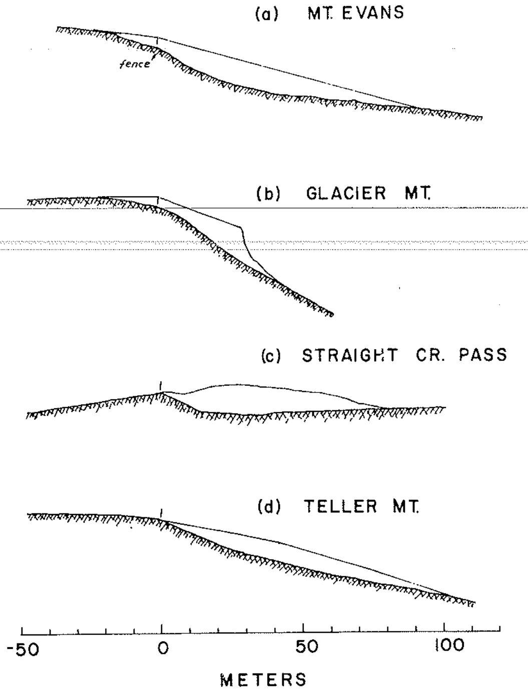

Figure 4. Snowdrift cross sections on 4 irregular terrain situations, showing variations of total drift length and snow accumulation (horizontal and vertical scale equal).

Case 3—A Snow Fence Located Leeward From a Rounded Ridge Crest

The pressure gradient changes from favorable to adverse near the crest. The fence is located in an adverse pressure gradient, and the results depend on the strength of the natural adverse gradient. If the lee slope is gradual and flow does not separate, results should be similar to those of Case 2, where accumulation and length were increased and the fence became buried.

If the lee slope is steep and flow separates, the fence fixes the point of separation, and a cornice forms behind the fence. In this situation, velocities in the reverse flow are strong enough to transport snow. The drift is then shorter and contains less snow than expected for the same fence on a horizontal surface. Such a condition was examined at Glacier Mountain near Montezuma, Colorado (Fig. 4b). The fence was 35 m lee of the crest and the lee slope was steep. Again the fence was buried in the drift in spite of the gap between fence and ground.

Case 4—A Snow Fence at a Sharp Ridge Crest

If a fence is located at the point where the pressure gradient changes from favorable to adverse, the fence effect is again increased by the natural adverse pressure gradient in the lee of the crest. As in Case 3, the resulting drift depends on the steepness of the lee slope; it is larger and longer if the slope is gradual, and smaller if the slope is steep enough to cause strong reverse flow. However, the favorable pressure gradient upwind of the fence maintains increasing surface shear stress, which causes snow erosion and leaves the fence free of the drift.

The drift cross section shown in Figure 4c was measured at Straight Creek Pass on the Continental Divide in Colorado. The depression lee of the crest filled in rapidly, and the lee slope was then gradual enough to allow a rather spectacular drift to develop.

Case 5—A Fence Located at a Break From Horizontal to Lee Slope

In terms of pressure gradients, this fence is located at a point where the gradient changes from zero to adverse. The fence effect is again strengthened by the natural gradient, and the results depend on the strength of the gradient. A cliff is an extreme example of this case; separation is well defined at the drop-off, and a cornice typically forms. With a more gradual lee slope, both total accumulation and maximum drift length increase. Measurements at Teller Mountain (Fig. 4d) are an example of the latter situation.

Although the configurations of terrain and snow fence location described are only a few of the infinite possibilities, a few generalizations may summarize this section: (a) Snow fences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain; (b) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift; and (c) fences located within an adverse pressure region should show effects that follow those given in statement (b), but usually become buried in the drift.

Statement (b) suggests that there is some terrain configuration that is optimum for accumulating snow behind a snow fence. The fact that there is a fence density less than 100 percent that gives maximum snow accumulation on horizontal terrain can be based on the same reasoning as statement (b). In both cases, the pressure recovery for optimum accumulation is more gradual than the maximum gradient that can occur. Perhaps pressure measurements on a fully developed snowdrift deposited on a horizontal surface would provide a starting place for model studies to determine if statement (b) is true, and at least the general configuration of the optimum situation.

Because favorable pressure gradients have been equated with windward slopes and adverse gradients with leeward slopes, one might wonder what is gained by considering pressure gradients in place of terrain gradients. There are at least 2 reasons. First, the pressure gradient is a basic parameter used to relate variables in the wind tunnel studies on development of turbulent boundary layers. To apply these studies to flow over natural terrain requires some idea of the natural pressure gradient. Second, the flow mechanism is governed primarily by the pressure gradient, and there is very little knowledge of the relationship between ground slope and pressure gradient. Scorer (11) has pointed out that the pressure gradient depends on the size and location of the lee eddy as well as the shape of the ridge. Perhaps a useful relation can be developed.

CONCLUSIONS

1. Changes in the shear stress distribution must be considered when snow transport theory is extended to irregular terrain.
2. Pressure gradient arguments and some field measurements support the idea that there is an optimum terrain configuration for snow accumulation. Information is not currently adequate to specify what the configuration would be.
3. Fences located within regions of adverse pressure gradient usually become buried in the snowdrift. These fences should either be designed to withstand snow settlement or be relocated near the start of the adverse pressure gradient.

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Model Technique for Controlling Snow on Roads and Runways

F. H. Theakston

Snow has always been a most difficult element to predict and also to control in areas where there is heavy accumulation. An open channel water flume and models have been used to predict consistently the patterns developed by falling snow. Light, white sand is used to simulate snow. Various densities of snow storms are created within minutes, and qualitative analyses are made for remedial measures. A wind tunnel study is carried out to ensure positive results.

Snow is an element of nature that displays many contradictory characteristics. It is both a nuisance and a necessity. It is both beautiful and ugly, depending on the conditions through which it is viewed. To some it is a hindrance to travel, and to others it is the only medium through which conveyance is assured. It is clean, it is dirty; it is almost weightless as a snowflake, but as a mass it can collapse large structures. Individually snowflakes are things of beauty, and it seems that no 2 flakes are alike in their intrinsic and delicate patterns.

Snow is, indeed, a fascinating element characterized by dual and often opposing tendencies; but perhaps the greatest and most distinguishing fact is that, although we know so much about the element snow, there are times when we know little or nothing.

The behavior of most elements of nature can be predicted through studies of recurring incidents such as wind storms, rain storms, and snow storms. In this respect, protective measures can be provided long before the storm arrives at the site. However, snow again does not conform to normal behavior because many of the problems created by snow occur after the storm.

The movement of snow particles or dry granules on the surface of crust or ice or frozen ground and the subsequent buildup is called "saltation." Accumulation of snow occurs at the bottom of a turbulent zone because the particles tend to drop out at the region of low velocity. Because turbulence occurs from an obstruction in the wind direction, it follows that predictions can be made for sites of accumulated snow. Furthermore, it is possible to cause drop out of snow by creating the turbulence where it is desired in the prediction plan.

Basically, control of snow is a matter of adjusting the energy of the wind that is the transporting agent. It is true that energy cannot be created nor destroyed, but it is also true that the total energy can be distributed in such a way that the total force is dissipated before the wind reaches critical zones. Experimentally, it is time-consuming and often unrewarding to study snow in the field, because there is no control of the variables. However, the resulting patterns are undeniably correct and the researcher can take advantage of the prototype when using laboratory procedures. For example, aerial photographs taken at 500-ft elevation provide a clear picture of problem areas on roads, runways, buildings, and parking lots; and the details are invaluable in the collection of laboratory data.

The laboratory procedure established at the University of Guelph utilizes an open-channel water flume to simulate wind. Because water and wind are both fluids having similar characteristics, it is possible to compare the fluids to scale. The chief advantage, however, is that the flow is decreased to an extent where observation of the particle movement can be used as a study medium.

The open channel is 25 ft long, 3 ft wide, and 18 in. deep at the observation section. The side walls are made of plexiglass. The steel entry area is 10 times the cross-sectional area of the open channel to conform with fluid dynamic principles. The supply of water comes from a constant head tank to give a steady rate of flow. The velocity of

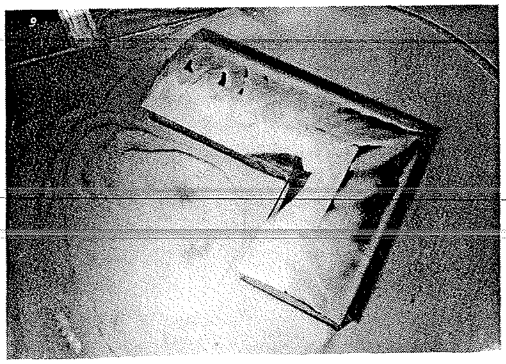

Figure 1. Typical snow pattern on the roof of a building with a valley (wind from right).

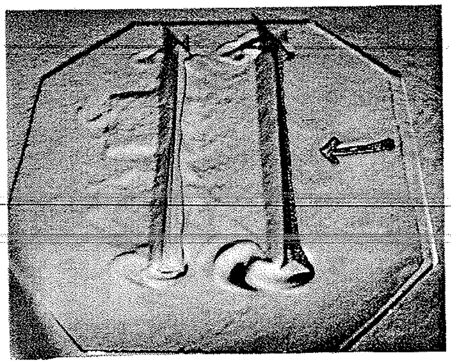

Figure 2. Solid triangular fences used to collect snow (wind from right).

the water, however, can be varied by raising or lowering a steel plate at the end of the flume. Normally the flow is at the rate of 3 cu ft/min. The discharge water is collected in a sump and pumped to the constant head tank for further circulation.

The snow is simulated by white Ottawa silica sand (density No. 100). It is injected in the water flume by means of a metering device to provide a dense, medium, or light snow storm as required by test. The storm is effective immediately and qualitative analysis can be obtained in a very short time. Obstructions to the wind, such as fences, trees, shrubs, and buildings are scaled (1 in. = 16 ft) and placed in the flume on a circular base so every wind direction can be observed during the tests (Figs. 1-4).

The model technique assures a quick, positive method of analysis with 100 percent results from a qualitative point of view. The exigencies of snow particles make it more difficult to determine results quantitatively with such accuracy, but certainly close estimates of depths can be made with sufficient success to be useful in design. The models used are often made from plexiglass because they can be scaled easily and assembled quickly with acetone chloroform and fixed to the circular base in the same manner.

Snow fences for roads and runways should be assessed for porosity, height, and location, though other considerations such as materials of construction, strength, durability, and cost are important factors (Figs. 5 and 6). It has been useful to establish a base from which all other comparisons can be determined. A solid fence provides clear characteristics with regard to accumulation of snow. There is always "cupping" action on the windward side due to the rotation of the particles as they

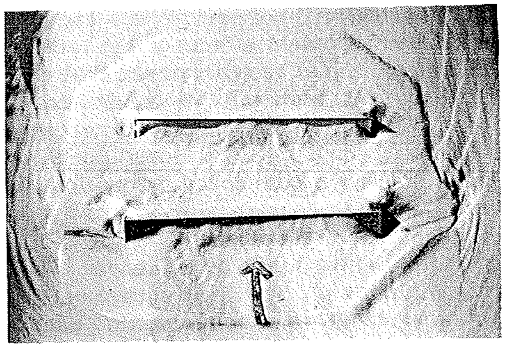

Figure 3. Solid fences 16 ft high collect snow in between (wind from bottom).

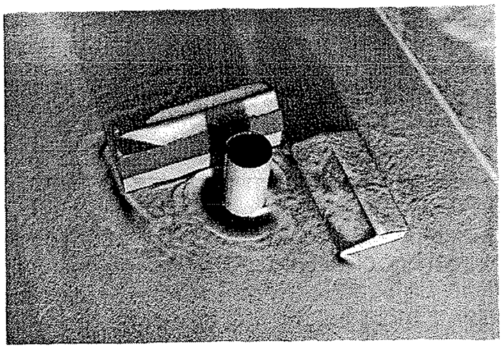

Figure 4. Studies around buildings indicate recurring patterns.

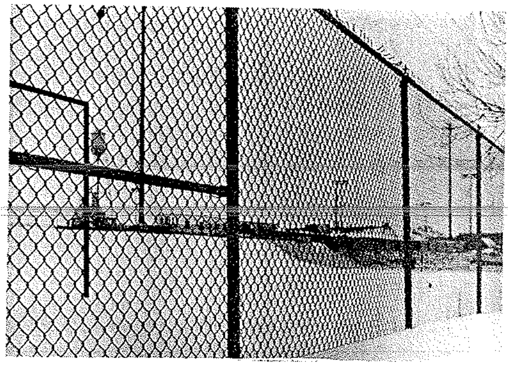

Figure 5. A steel wire fence is not very effective as a windbreak or snow barrier.

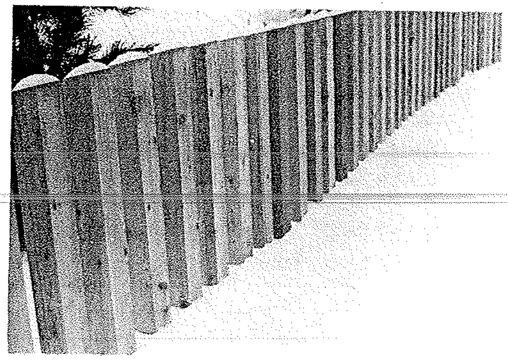

Figure 6. Decorative fence with 50 percent porosity showing energy dissipation at each opening.

rebound from the obstruction. This action continues until a "bridge" is constructed on a slope to the top of the fence. When the bridge is completed the usefulness of the fence becomes less, and the "ramp" effect tends to carry particles over the obstruction to drop out on the leeward side immediately behind the fence. Even extremely low obstructions to the wind will create this effect, but the most suitable solid fence is one with a height of 6 to 8 ft and placed a minimum of 35 ft from the area to be protected, such as a road or runway strip. It is likely to be more effective if placed 60 ft from the area where space is available. By using the solid base as a standard, porous fences have been studied with the specific purpose of determining efficiencies for roads and runways.

The conventional snow fence used for highways consists of wood slats spaced vertically; it has served a useful purpose but has definite limitations that must be recognized by the user. The location of the fence has not been established by any scientific approach but rather by intuition or to correct an obvious accumulation area. It is, at best, a hit-or-miss method and often has caused as much harm as good. The primary purpose of the porous fence is to permit some wind through the open section while retaining snow on the windward side. A 50-50 percent porosity is probably the best ratio, but this depends entirely on the condition to be remedied by the protective device.

A snow fence of the conventional wood slats and wire type is usually relatively low in height, and the snow reaches the top of the fence with little snowfall. When this situation occurs a ramp effect over the fence will not only deposit snow on the road or runway but will, in fact, cause turbulence and will often create zero visibility hazardous to ground vehicles and airplanes.

Fences of varying heights and porosities have been studied with some rather interesting and useful conclusions. Fences with either horizontal or vertical openings with a ratio of 50 to 50 percent will provide some protection and will not accumulate snow to the top of the fence. However, this porosity will cause turbulent effects on the leeward side of the fence resulting in a heavy buildup of snow. It has been observed that considerable gusts are built up at the highway or runway when high velocity winds are passing through the fence. Higher porosities (e.g., 60-40, 70-30, and 80-20 percent) have been more effective in control of snow than those of equal open and closed portions.

An interesting development in snow fence design has been introduced by one industry in the form of plastic, which is durable, is strong, and has considerable longevity. Diagonal openings shaped like a rhombus create turbulence behind each opening in the fence and the venturi-like action deposits snow on the leeward side of the fence. The fence is excellent provided the proper porosity is maintained, but it is recommended that a fence height of 4 to 6 ft be used for heavy snow areas. The fence is also useful in areas where sand blowing is a problem because it offers similar remedial measures.

Open hangars on airfields or landing strips can be seriously impeded by snow. Often orientation of the structure is the solution to this problem, but it must be emphasized that any obstruction to the wind, including buildings, will cause turbulence with resulting accumulation. This is particularly true with gable-roof structures because the vortexes initiated at the ridge continue to the ground in line with the sloping roof.

Snow particles within the resulting turbulent zone will be drawn into the open structure, and usually a bank of snow will be deposited immediately in front of the hangar. There are several ways to remedy this occurrence; one is to construct a solid fence on the windward side of the building. Another is the construction of a "swirl chamber" as close to the windward side as possible. The swirl chamber is simply a solid fence constructed 16 ft from the front of the structure and 16 ft parallel to the end of the building forming a box-like area. The fence can be built any length once the box-like section has been formed.

Studies of the action of snow in and around hangars and other buildings have indicated a need for the designer to be very conscious of the action of the elements and to take steps in the exterior design features to protect the user against undue accumulation effects. Prediction of snow buildup is easily and quickly made from the model technique and is an effective medium for engineers, designers, and architects.

Informal Discussion

L. G. Byrd

Have you used any highway structures, facilities, or appurtenances in your modeling.

Theakston

No. We did some highway bridges because somebody wanted to find out what happened to the snow on the bridge surface, and we found out. We also found out how to determine the scour of the abutments by using the sand in the base of our model. But other than that, the highway people have not come to us yet, and we have not gone to them.

Byrd

I presume they are invited.

Theakston

They are invited, yes.

L. David Minsk

Your laboratory work would be amenable to quantitative studies because you control all of the factors and determine, for instance, the effectiveness of various aperture ratios of the fence, proper height, and opening at the bottom—those things that can be quantified.

Theakston

Yes, I think so, and this is our next step. We have done some of that already, but we have a long way to go. I really do not know enough about the quantitative aspects myself, and so I would like some assistance on that. We do consulting work on this outside of agriculture. If it is an agricultural problem, it is done for nothing; but if it is something else, then it can be done on a consulting basis.

Byrd

How close were the patterns of the models and the actual physical structures you made?

Theakston

These models were made on $^1/_{16}$ scale, and then we went back and confirmed this on the site and from aerial photographs. The patterns were always the same, and it does not matter really what the velocity of the wind is. If it is a high velocity wind, there is less buildup, particularly in and around buildings. With the slow velocity, there is more chance for buildup, and that is the only difference. The pattern is about the same.

Principles of Snow Removal and Snow-Removal Machines

Karl Croce

This paper discusses the principles for snow removal and describes a snow-removal machine whose design is based on these principles. The machine can remove snow 3.5 m deep in one operation. For many years it has proved to be very useful on roads and airports.

CASTING OPERATION

Snow-removing machines cast the snow away; therefore, the snow must be accelerated to a certain speed within the machine. The farther the snow is to be cast, the higher this speed must be. The cast is farthest when this speed moves the snow stream at an angle of 45 deg at the beginning of the cast. At this angle the casting distance is given by the ratio

$$W = \frac{u^2}{g} \tag{1}$$

where W is the casting distance in meters, u is the starting speed of the snow in m/sec, and g is the constant gravitation (9.81 m/sec^2). In this case, we have not taken account of the air resistance. Tests with machines, the impellers of which are equipped with radial shovels, have shown that at an angle of 45 deg at the beginning of the cast the ratio

$$W = \frac{u^2}{g} - 0.0023\ u^3 \tag{2}$$

is obtained for the reached casting distance W. Here 0.0023 u^3 is the influence of the air resistance, which is to be considered only in the case of long casting distances. Both ratios are shown in Figure 1.

Casting distances of approximately 8 to 15 m are necessary for removing snow on roads. In most cases, 8 m are sufficient, and distances longer than 15 m are seldom needed. The point is to build a machine that has the highest efficiency when casting 8 m, although some losses can be registered when casting 15 m. A casting distance of 8 m corresponds to a starting speed of the snow of 10 m/sec, and of 15 m, to approximately 15 m/sec. The machine must give this speed. Higher speeds are not necessary because then the snow is thrown farther than needed, and the energy used is lost.

In order to throw a weight of G kilos over a casting distance of W meters, a mechanical energy of A mkg is necessary, which is given by

$$W = 0.5\ G\ W \tag{3}$$

In this and in the following we have not taken account of any losses.

If G kilos of snow are to be thrown over a distance of W meters each second, then the needed energy N in hp is

$$N = \frac{G\ W}{150} \tag{4}$$

If a certain energy N is provided in a machine, then a snow weight equal to

$$G = \frac{150\ N}{W} \tag{5}$$

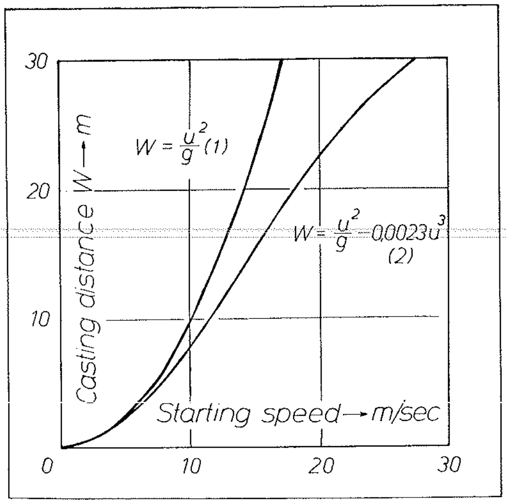

Figure 1. Casting distance of impellers with radial shovels at different speeds at the beginning of the cast.

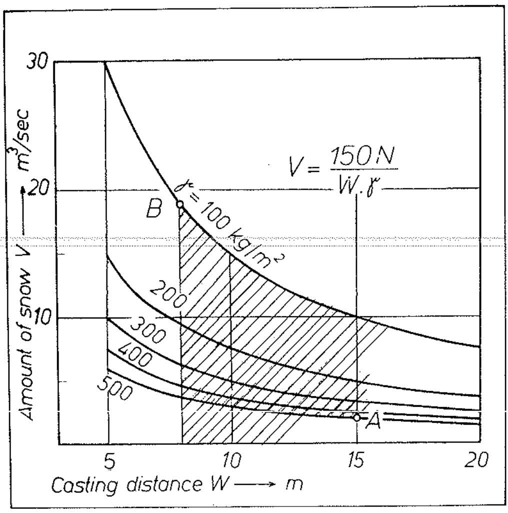

Figure 2. Amounts of snow removed by driving force of 100 hp at different casting distances.

can be discharged every second over W distance. In order to find out more, we have to know the possible amount of snow to be removed and the possible volume to be removed. These are obtained as follows:

$$V = \frac{150\ N}{W\ \gamma} \qquad (6)$$

where γ indicates the sepcific weight of snow in kg/m^3.

Let us now go into the details of how these ratios are obtained according to the laws of casting or general mechanics. Figure 2 shows the possible amount of snow to be removed with a driving force of 100 hp at different throwing speeds between 5 and 20 m. The figure shows very clearly how much the amount of snow to be removed with a certain driving force depends on the casting distance and the weight of the snow. At a casting distance of 5 m and a specific snow weight of 100 kg/m^3, 30 m^3 can be removed each second; if the specific weight of snow is 500 kg/m^3 and the casting distance 20 m, 1.5 m^3 can be removed each second. Casting distances between 8 and 15 m are hatched in Figure 2.

DIRECTION OF CAST

The job of snow-removing machines is to remove snow from trafficways and discharge it to the sides. This happens with the least possible expense of energy when the snow can be discharged at a right angle to the direction of traffic. If the throw is oblique to the direction of traffic, as it is with some machines, the casting distance, and therefore the energy, is more than needed. If the direction of the cast is inclined 45 deg forward, then the needed casting distance for attaining the same actual distance is increased approximately 1.5 times.

HARDNESS OF SNOW

It is generally known that fresh snow is soft and loose. It is composed of ice particles that lie loosely on top of each other. The longer the snow lies after falling, the harder it gets. The snow particles are packed closer together and freeze, so that the snow gets harder. This depends largely on the temperature. In cold weather the snow

TABLE 1

SWISS HANDTEST FOR HARDNESS OF SNOW

Hardness		Object That Can Be Pressed Into Snow at 3 kg Pressure	Shear Firmness (kg/dm^2)
Grade	Description		
1	Very soft	Fist	0 to 1
2	Soft	Stretched hand	0.5 to 10
3	Medium hard	Stretched finger	5 to 15
4	Hard	Pointed pencil	10 to 30
5	Very hard	Knife blade	30 to 50

stays soft, but it gets hard quickly if the temperature changes rapidly from cold to warm to cold because the melt water covers the snow particles and acts as a kind of glue as soon as the temperature gets cold again.

Different measuring instruments are used to measure the hardness of snow. The "handtest," developed in Switzerland, is mostly used for snow-removing purposes (Table 1).

CUTTING SNOW

When snow is removed, it must be picked up by the machines and conveyed. The top layer is cut, and picked up first. The mechanical energy needed for this depends on the hardness of the snow. How much energy is needed was determined by some tests with a snowcutter at different speeds in different hardnesses of snow. Figure 3 shows the necessary mechanical energy for cutting 1 kg of dry snow at a vehicle speed of 600 m/hr, cutting speeds of 3, 9, and 18 m/sec, and a cutting angle of the 4 cutting knives of 20 deg. At a cutting speed of 9 m/sec, soft snow requires a cutting energy of 2 mkg/kg; hard snow, 9.5 mkg/kg (almost 5 times as much); and very hard snow, 25 mkg/kg (12.5 times as much). This difference is more pronounced when one considers how far 1 kg of snow could be thrown with the energy needed to cut it. Soft snow could be thrown 4 m, hard snow 19 m, and very hard snow 50 m. The cutting energy for hard and very hard snow is much higher than that needed for casting. On the other hand, hardly any energy is needed for cutting very soft snow.

The cutting energy increases with the hardness of snow. For this reason the snow should be removed as soon as possible after falling. Also one should work with the smallest possible cutting speed because few knives and a slow cutting speed result in thick pieces of snow and save cutting energy.

This all means that the organization of snow removing on roads that have to be kept clear permanently should be adjusted according to the techniques for removing soft snow, and the machines should be built accordingly. It is very suitable to possess some blade-type snowplows and a certain number of machines that remove soft snow especially well. Thus, it is possible to keep the road system clear of snow with the least possible expense in energy, because the snow does not remain long enough to get hard.

This is the way the road system in Bavaria is being kept clear of snow with success in spite of the heavy snowfalls, Bavaria has 932 km of expressways, 7,200 km of main roads, and 13,500 km of secondary roads

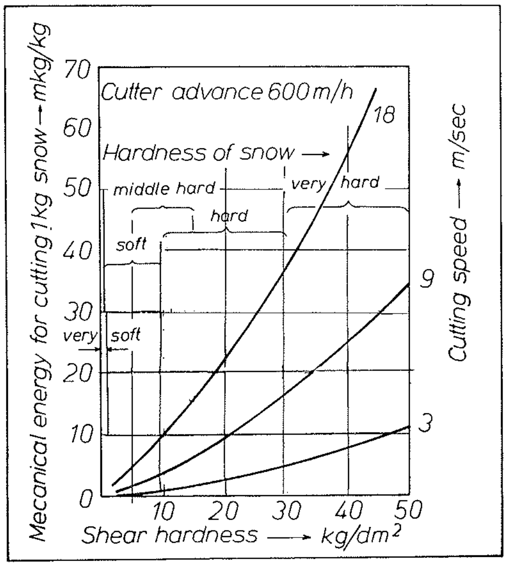

Figure 3. Cutting snow of different hardnesses with cutting speeds up to 18 m/sec and a vehicle speed of 600 m/hr (approximate values).

at an elevation between 250 and 1,800 m. Each machine is correctly matched to the type of snow, whether hard or soft, that it removes.

INTERNAL FRICTION OF SNOW

Snow becomes harder under mechanical stress. For this reason much energy is required to change its form. Under such stress the snow loses its original characteristics. Particles are pressed closer together, and the warmth caused by their rubbing and grinding welds them together. The needed energy to change the form cannot be recovered as with an elastic body; it is lost and only causes the snow to become harder and more compact.

For this reason heavy losses are caused by the deviation of the snowstream. Tests have shown that a snowstream that is deviated 90 deg loses half its energy because of the internal friction of the snow. The form of snow is plastically changed and exposed to centrifugal forces, which press it sideways. In addition, the stream is compacted in length because its speed decreases steadily. Snowstreams should not be deviated. The snow should be discharged in the direction it is being moved. Similar processes happen when the snow must be deviated within the machine. That is the case when the snow is picked up at a right angle from the advance of the vehicle and then discharged in another direction. The energy to pick up the snow is changed into internal friction, increasing the specific weight and the temperature of the snow, and is lost for the cast. Tests have shown how heavy the losses caused by such processes are. Samples of snow with specific weight γ_0 were pressed together to specific weight γ_e in cylindrical containers. The mechanical energy in mkg necessary to bring 1 kg of snow up to the heavier specific weight was obtained.

Figure 4 shows the result. For the single γ_0 the curves for the increasing γ_e are above each other. This means that the mechanical energy for compressing snow increases with increasing final weight. Each curve has a special highest value that, by γ_0 weight, lies between 80 and 100 kg/m^3. Naturally, loose new snow requires the most energy to be compressed. Most of the fine crystals of this snow must be broken up so that they can be compacted. Crystals of less fine snow do not require so much breaking up and slide more on each other when compressed.

The curves shown in Figure 3 were made for dry snow at -5 C. When the temperature is higher, the figures decrease; and when the temperature is lower, they increase. The ice that composes the snow crystals is then softer or harder. Water in snow has the same effect as a lubrication fluid and causes less energy to be required for compression.

Experience shows that new snow in a snow-removing machine increases from an original specific weight of 100 kg/m^3 to approximately 350 kg/m^3 while being conveyed. Snow that weighs 200 kg/m^3 at the beginning increases to a weight of approximately 450 kg/m^3. If this compression were caused only by pure pressure, then each kg of snow would need a compression energy of 5 or 6 mkg/kg. With the same energy, the same kg could be cast 10 or 12 m. Similar losses occur whenever the direction of the snow is changed within the machines. The real compression energy needed is often more. It has become clear that the energy lost in compression is just as much as that needed for casting snow.

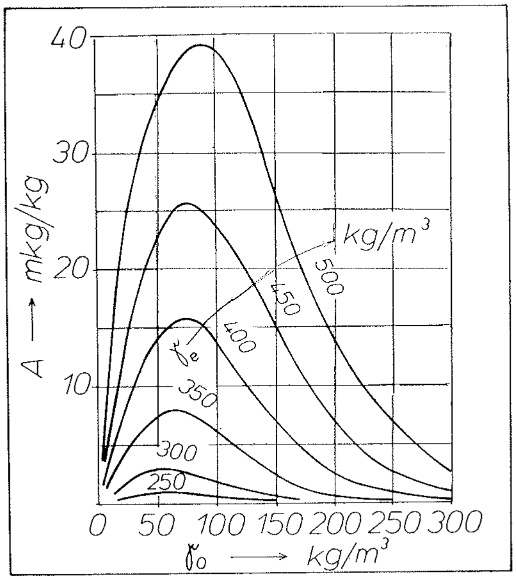

Figure 4. Mechanical energy for compressing dry snow from γ_0 to γ_e.

IMPELLERS

Most snow-removing machines have impellers with radial shovels for accelerating and discharging the snow. These impellers turn in a casing that covers the range of impellers and that has an opening through which the snow will be discharged. The snow is conveyed in the direction of the impeller shaft and then picked up by the shovels. The centrifugal force causes it to slip toward the tips of the shovels all the way against the casing. Then the tips of the shovels force it to slide on the inside surface of the casing all the way to the opening, where it can leave the casing.

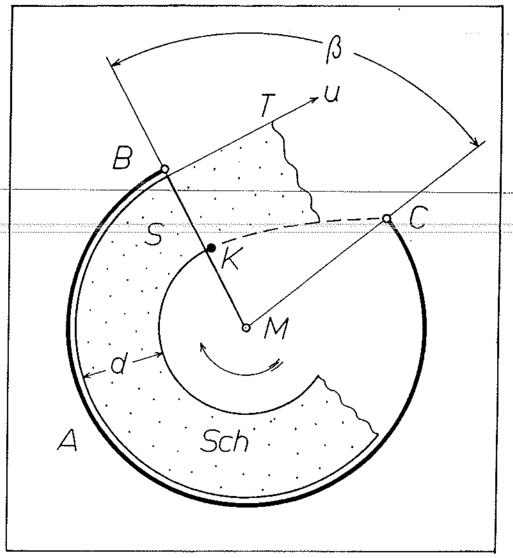

Figure 5. Movement of snow in impellers.

Figure 5 shows a cut at right angle to the impeller shaft. The opening B-C in casing A stretches over the centri-angle β. The shovels S, of which only one is shown here, are leveled, radial surfaces and revolve around the middle point M of the impeller in the direction of the arrow. In this figure, the shovel is shown so that its outer edge has reached the beginning of the opening B. The dotted circle Sch represents the snow that the other shovels, which are not shown here, force into a circular movement.

In the areas where the casing is shut, the snow can follow the centrifugal force only if it compresses under its action. When it reaches the opening B-C, it can leave the impeller toward the outside.

The outside layer of the ring has the circumferential speed u of the impeller. At B it starts leaving the impeller along the tangent T. While the shovel moves farther in the direction of C, other layers that are farther inside also reach the outside edge and attain this speed. They fly tangentially. In the meantime the shovel has moved on farther; these tangents form a flat angle with the course of the outer layer. The courses of the single layers tend to fly apart from each other in a fan pattern. The speeds that these layers attain are not exactly the same as the circumferential speed that each of the single layers attain at the outer edge of the shovel. This component is not large. It presses the fan formed by the cast back together.

There is a relation between the centri-angle β of the opening and the radial thickness d of the snow layer. The thickness d should be only so much that the point K of the inside range of the snow layer Sch along the dotted line K-C attains the outer edge of the shovel when this reaches the casing again at C. Research has proved that this relation is purely geometrical and does not depend on the speed of the impeller. The thickness d of the throwable snow layer, which is formed in the impeller, depends only on the opening in the casing and not on the revolution number of the impeller. When calculating d, which cannot be done in detail here, we obtain

$$d = R - r_0 \tag{7}$$

whereby

$$r_0 = c\,R \text{ and } d = R(1 - c) \tag{8}$$

can be set. The figure value of (1 - c) in relation to the centri-angle β of the opening is shown in Figure 6. For $\beta = 70$ deg, as is often the case, we obtain $(1 - c) = 0.46$ and

$$d = 0.46\ R$$

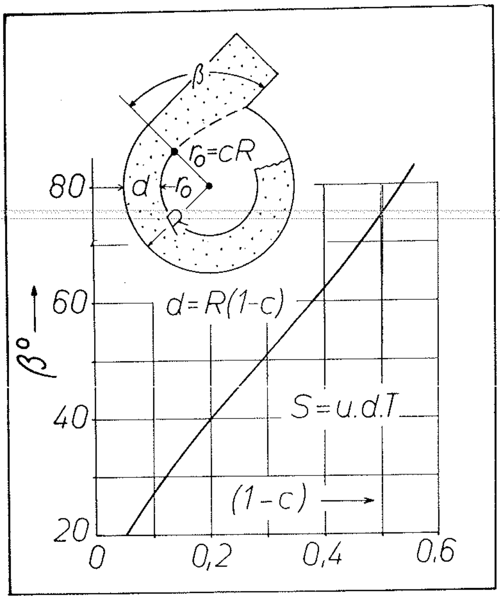

Figure 6. Auxiliary values for calculating the swallowing capacity S of the impellers.

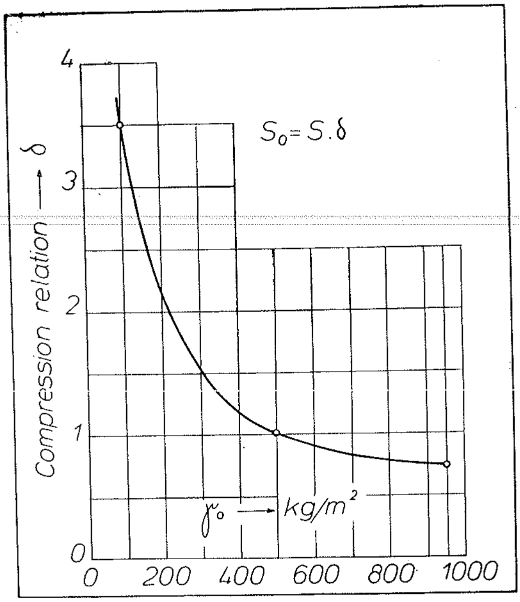

Figure 7. Amount of snow S_0 that has been removed from trafficway with specific weight γ_0 in relation to swallowing capacity S of machine.

CAPACITY

The thickness d is an important factor for the largest amount of snow, S, that such an impeller can convey. This amount of snow is called "swallowing capacity." If more snow is fed into the impeller than it can swallow, the thickness of the circular ring exceeds the limit determined by the opening in the casing. The inner layers cannot be discharged while the shovel passes by the opening. They remain in the impeller and jam and clog it. The whole impeller then contains one mass of compressed snow, and it is a big job to empty it. The swallowing capacity of an impeller with a certain right angle opening of the cast is a result of the permissible thickness d of the snow layer to be discharged, of the height of the impeller shaft, and of the speed with which the snow leaves the impeller. Because it does not differ much from the circumferential speed u of the impeller, the swallowing capacity can be calculated accurately enough with the circumferential speed.

$$S = u\ d\ T \tag{10}$$

It increases linearly with u. Because the casting distance also increases linearly with the circumferential speed of the impeller, the same linear relation must exist between the swallowing capacity and the casting distance. The farther the snow is cast, the more the impeller can swallow.

Many snow-removing machines use this in order to transform their driving power into casting distance. Because the impellers swallow too little with the required low number of revolutions, they cast farther than needed while working with a higher number of revolutions. They have a slightly higher capacity but use more energy in vain because they transform their power into a long cast, which is not needed. It is better to build machines that swallow enough to take advantage of the driving power and that operate with a low number of revolutions.

An impeller that has to cast the snow to a certain distance must have a certain circumferential speed and can convey only a certain volume of snow in each time unit. It depends on the centri-angle of the opening for the cast and on the height of the impeller shaft.

The calculated swallowing capacity results from the snow that leaves the machine in the snowstream. This means it is a result of compressed snow. To find out the quantity of snow that the impeller can pick up requires that the compression, which comes about in the machine, be taken into account. There have been no tests made on the compression relationship in such machines. One must relay on estimations. These are more easily made by observations. New snow with a specific weight of 100 kg/m^3 is brought up to 350 kg/m^3 in a snow-moving machine. Compression is less with heavy snow; snow with a specific weight of 500 kg/m^3 will not be much more compressed. Besides, it is known that ice removed with 950 kg/m^3 is loosened up to approximately 700 kg/m^3. This makes it possible to show the relation between the compression, δ, and the specific weight, γ_0, of snow in Figure 7. If the amount of snow, S_0, to be removed by such impellers is calculated with the swallowing capacity S, it is a result of

$$S_0 = S\ \delta \tag{11}$$

REMOVING SNOW

Casting distances of 8 to 15 m require adjustable circumferential speeds of 10 and 15 m/sec. Of course these circumferential speeds should be obtained with the driving engine for the impellers always turning at full speed so that the machine removes as much snow as possible. Combustion engines, usually used in such machines, give full efficiency only when running at a certain speed. A change gear is necessary between the engine and the impellers.

During snow-removal operations, the cast should always have the required length. The impellers must revolve at a constant speed. The amount of snow that can be removed with the available energy changes with the specific weight of the snow to be removed. The speed of the vehicle must adjust itself to the snow. Also the changeable snow uses all the available power in the removing system. The driving power for the speed of the vehicle must permit repeated adjustments to the number of revolutions.

It has proved best to equip the machines with 2 engines. One engine keeps a regulated and constant speed with the highest output that permits a cast of the required distance and that is adjustable because of a transmission. The other engine is used to regulate the vehicle speed so that the snow-removing system always picks up and conveys to its highest capacity.

CLEARING CAPACITY

The snow-removing machines should be judged according to how well they can do their jobs. For the mechanical parts, a quality measure should determine the effect of the energy. It should tell how quickly a machine can remove the snow from a trafficway.

The more snow a machine can remove in each time unit, the quicker the road is clear. This could mean ever bigger machines are needed. This, of course, is not our intention. We need a way to measure that does not depend on the size of the machine. Such a way is obtained when the amount of snow removed in a time unit is divided by the output of the machine. This measure is called "clearing capacity." The higher the figure is, the better the job done by the machine in the time allowed.

The amount of snow G in tons that has been removed by a machine can be calculated in m^3/hr as a result of research of snow depth, clearing width, and advance. It should be recalculated into tons/hr with the specific weight of the snow, because then the specific weight of snow does not play an important role anymore. If that is done, then the specific weight of the snow should be given in order to calculate the volume that has been removed.

The driving power also determines the clearing capacity. It depends on the engines that are used. The clearing capacity R is a result of

$$R = \frac{G}{N} \tag{12}$$

This gives the number of tons of snow removed by the mechanical energy in the drive of the machine. In addition, the hardness of the snow has to be given. The harder the snow is, the more mechanical energy needed for loosening the snow. This energy is lost and cannot be used for conveying the snow. Therefore, the measure is not complete if the hardness of the snow is not given.

The clearing capacity we have expressed here is an absolute measure for the efficacy of the machine in different snow conditions. If snow-removing machines are always judged according to this clearing capacity, it will be advantageous for the further development of the machines. The engineers must try to build a machine that will clear as much snow as possible with the least possible driving power. This is attained by keeping the casting distance as short as possible. Then the driving power is transformed into a short cast for much snow and not into a long cast for little snow. The casting distance should be just enough to keep the trafficways clear. Eight meters are usually sufficient; often fewer meters may suffice.

The complete nominal power of the engine should be used for the calculation of the clearing capacity. This will force the proper design of the clearing system. This system should be able to transform the full power into conveying movement even with a very short cast. The clearing system must have a sufficient swallowing capacity even with a very short cast, that is, with a small circumferential speed. This means that all parts of the machine must be able to handle the amount of snow being removed; that is, they must be able to pick up, convey, and discharge the snow without jamming and clogging. Otherwise, the amount of snow picked up by the impellers cannot be discharged unless the opening and other passages through which the snow is conveyed are large enough.

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Figure 8 shows a large snow-removing machine that meets these requirements. The machine is equipped with a diesel engine with 275 hp or more for the snow-removing and casting systems and a diesel engine with 200 hp for the vehicle. The latter is equipped with a transmission and regulates the speed of the machine by acting on all 4 wheels. The speed can be regulated between 118 and 64, 000 m/hr. The vehicle is steered with the rear axle, so that the sideway directed steering power with long lever arms influences the front part. This and the short distance between the axles (3.6 m) permit the machine to drive around sharp curves even in deep snow. The clearing system is equipped with two impellers with diameters of 1.17 m (wheels with shovels) located side by side and opened toward the front. The impeller shafts are in the direction of travel. The 2 circular-shaped working profiles are completed by a casing that forms a rectangular profile with a clearing width of 2.9 m. The height of the casing is 1.39 m. Each impeller is equipped with 4 strong shovels. The inside edges of these form a hollow that becomes narrower toward the back. The shovels are formed like spirals, so that they act as a screw in the snow under the advance of the vehicle, without accelerating the speed of the shafts. The losses caused by acceleration of the shafts are very light. The impellers, with a depth T of 0.62 m, run in cylindrical casings with tangentially arranged casting chutes. The rectangular opening where the chute is fitted

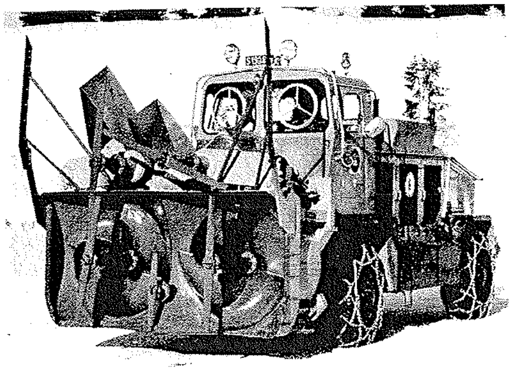


Figure 8. Snow-removing machine with clearing height up to 3.5 m and clearing width of 2.9 m.

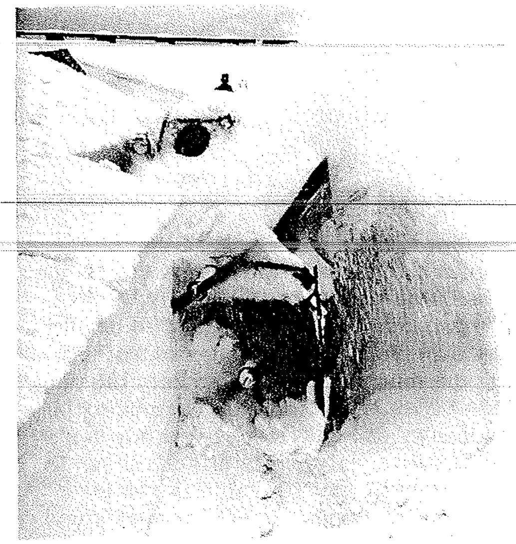


Figure 9. Snow-removing machine in operation.

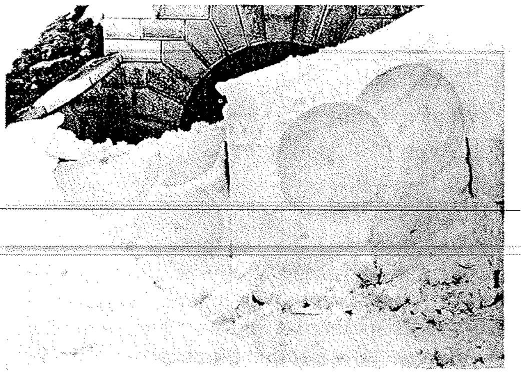


Figure 10. Cleared road with clearing profiles in hard snow (snow depth 3.5 m).

to the casing stretches over the centri-angle β at 71 deg. The casing of each impeller and the chutes pivot around the axle of the impeller, so that the snow can be discharged to the right as well as to the left. A changing gear is installed in the drive of the impellers so that adjustments can be made for different casting distances.

The picked up snow is moved sideways without having to be deviated. There are no losses caused by deviation. The streams are directed at a right angle to the advance. The obtained casting distance is used fully.

To loosen harder snow, a strong propeller 1.30 m in diameter is installed on the shaft extensions of the impellers. The snow is loosened in front of the impellers. The precutting propeller cuts thick pieces of snow so that no energy is lost in cutting small pieces. These precutters, together with a third precutter in the center down toward the point of the casing, permit the machine to be used also for cutting and removing very hard snow. This sort of snow can also be removed quite continuously at a slow speed.

Above the casing the clearing head carries additional precutting propellers with 1.50-m diameters. These are mounted on articulated arms that permit adjustments to the height and the distance between the propellers. These precutters are driven much slower than those on the impeller shafts, so that they cut bigger pieces of ice. Thus, little energy is needed for loosening the snow. The cut snow falls down in front of the impellers where it is picked up and discharged (Figs. 9 and 10). When these additional propellers are adjusted to full height, the clearing height is 3.5 m. It is then possible to clear snow with this depth continuously without the machine having to climb on top of the snow. The author knows of no other machine that can remove snow at such depths in one operation. All adjustments of the clearing system are operated hydraulically without having to interrupt the job.

These machines have been working for quite some years in areas where heavy snowfalls are common. They keep roads and railways free of snow during the winter and are also used in the spring to clear pass roads that have been closed all winter. These machines are also made with very long casting distances for use at airports. There are also very small machines that can be pushed by hand. They are being used in many countries all around the world.

Informal Discussion

A. G. Clary

What are the relative merits of this type of machine compared with those of the Snowblast type of machine?

L. David Minsk

This is one of the few plows that has been developed based on scientific principles. Dr. Croce began his study of snow in 1936 and continued it during the war at the Bauhof fur den Winterdienst at Inzell, Bavaria. I have seen this machine operate very effectively in low-density snow. The precutters or "vorschneider" are designed to handle a dense snow situation. More often than not, in my experience, it requires extremely precise control by the operator to avoid crowding the machine too rapidly into the snow. When this happens the shear pins in the precutters break, and then they become a liability. The effectiveness of this machine in low-density snow is unquestioned in tests that have been run in Germany, Switzerland, and in this country. Its effectiveness in higher density snow is so much dependent on operator skill that its value is reduced. The horizontal auger type, as represented by the familiar Snogo, is effective to some extent, but again it densifies the snow as it moves it across the entire front face to reach the impeller.

The Rolba principle, as represented by the Snowblast (its called the Rolba system in Europe) is effective in high-density snow because of the milling principle under which it operates, as is the Peter plow which is also a Swiss development. The Schmidt plow is similar to the Peter plow. The relative effectiveness of these plows has been shown in various tests. However, each manufacturer can point to some tests that will substantiate his claims. You have to evaluate them yourself.

Snow-Removing Performance of the Snowplow Truck

Yasuyuki Tanaka

Field studies of the performance of a 4-wheel-drive truck with snowplow produced the following results: (a) Working resistance of the truck consists of the truck's rolling resistance that varies with its speed, sliding resistance of the snowplow, and snow accelerating resistance expressed as a square of the truck speed; (b) at a truck speed of less than 7.5 mph, snow-removing performance of the one-way plow is not effective because the plow pushes snow without throwing; (c) snow-removing efficiency of the plow falls as the square of the truck speed; (d) the distance snow is thrown increases with the square of the plow speed; and (e) the plow with a conical surface performed better than one with a cylindrical surface.

In order to remove new snow from the surface of roads and runways, many straight plows mounted on 7- to 10-ton capacity trucks of 4-wheel-drive are used in Japan. Tests were conducted in the winters of 1965-1966 and 1966-1967 to ascertain the performance of a truck equipped with a snowplow having the capability of removing snow 5 to 20 cm deep at speeds of 15 to 30 km/hr. The tests were carried out on the test road at the Institute of Snow and Ice Studies located at Nagaoka in Niigata Prefecture. Tests were made on National Highway Route 17 running along Yuzawa, also in Niigata Prefecture, and at Aomori Airport in Aomori Prefecture. Because of the difficulty of controlling natural conditions such as snow density, air temperature, wind, and road surface condition, considerable scatter appears in the data. This report presents chiefly the results obtained in Aomori Prefecture.

TEST CONDITIONS

Truck and Snowplow Used in the Test

The truck used for the test was a dump truck modified for the attachment of a snowplow and equipped with a small hoist to facilitate the changing of test plows. The principal dimensions are given in Table 1.

Three types of snowplows were used. Type A, most commonly used, is a one-way plow with conical surface. Type B is an angling plow with cylindrical curved surface whose plow angle may be changed horizontally. Type C is an angling plow with a cylindrical curved surface whose plow angle and also throw-out angle may be changed. The tests were chiefly made by using Types A and C. Table 2 gives the principal dimensions of each plow.

Items and Methods of Measurement

Force required for removing snow was determined by measuring the hydraulic pressure of the cylinders attached to the 2 plow push bars. The engine horsepower was calculated from the reading of a torquemeter by employing wire strain gages and a tachometer attached to the drive shaft. The truck speed was measured by a fifth wheel. These data were recorded on a recorder located inside the truck cab.

Density, temperature, and volume of snow on the test area were measured in advance of the test. After a test run was made, the volume of any residual snow was measured and deducted from the volume that had been measured in advance. Measurements were taken every 5 to 10 m of running distance.

TABLE 1

SPECIFICATION OF TEST TRUCK (WITHOUT PLOW)

HINO ZH 10D Dump Truck	HINO DS 30 Diesel Engine
Length, 8,010 mm	Rated horsepower, 150 hp at 2,400 rpm
Width, 2,450 mm	Maximum torque, 50 kg-m at 1,600 rpm
Shipping weight, 8,330 kg	Transmission, 8 speeds forward and 2 speeds reverse
Total weight (with measurement device), 8,900 kg	Drive, 4 by 4, all-wheel
Maximum speed, 69 km/hr	Tire size, 1000-20, 14 PL
Turning radius, 9.7 m	Crane capacity, 2-ton hydraulic

TABLE 2

SPECIFICATION OF TEST PLOWS

Item	Type A	Type B	Type C
Plow	One-way	Angling	Angling
Snow clearing width, mm	2,550	2,940 at 60-deg angle	2,600 at 60-deg angle
Plow height, mm	1,150 left, 600 right	1,080	1,100 at 50-deg throw-out angle
Plow angle, deg	55	30 to 70	50 to 70
Throw-out angle, deg	-16.5	19	20 to 60
Plow weight, kg	450	638	400
Plow surface shape	Conical	Cylindrical	Cylindrical

The length of run was varied according to the working speed, but generally, it was 10 to 40 m. Distance required for a high-speed test reached 300 m to provide an accelerating distance, a preparatory measure section for attaining power balance, a measurement section, and a braking distance.

The behavior of the removed snow was also analyzed by high-speed 16-mm motion pictures, and the cast direction and distance were measured by marking the snow with ink.

SNOW-REMOVING PERFORMANCE OF SNOWPLOW

Resistance on Snow-Removing Truck

In addition to the running resistance general traffic vehicles have, snow-removing trucks have added the resistance caused by snow removing. The resistance is classified for practical purposes into 3 kinds: running resistance of the truck body itself, R_r; resistance of the snowplow sliding over the snow face, R_s; and resistance of snow-casting (snow-removing resistance), R_p.

Of these resistances, R_r is composed of rolling resistances, aerodynamic resistance, grade resistance, and accelerating resistance, as in all vehicles. The grade and accelerating resistances are transient, and aerodynamic resistance is also when it is outside the speed limit of a snowplow truck. Because it is 3 percent or less, it is excluded here. The rolling resistance is usually expressed by the following formula:

$$R_r = \mu_r W_T \tag{1}$$

where

R_r = rolling resistance;
μ_r = coefficient of rolling resistance; and
W_T = weight of vehicle.

μ_r is dimensionless and changes according to the tire pattern, inflation pressure, road conditions, and speed; it is usually 0.1 to 0.2 for an automobile tire. In the present test where 4-wheel-drive and chains on all tires were used, it is presumed that the values will be quite large compared with those for normal trucks.

Sliding Resistance of Plow

The resistance in sliding over the road surface may be expressed as

$$R_s = \mu_s W_s \tag{2}$$

where

R_s = sliding resistance of snowplow;
μ_s = coefficient of sliding resistance of snowplow; and
W_s = weight upon cutting edge or shoe of snowplow or both.

μ_s has different values according to road conditions and the form of the plow contacting the ground. In the present test, the ground contacting part was a cutting edge only, and no shoe or caster touched the ground. The tests were made under different conditions where snow or ice lay over the entire or partial roadway. It is known that μ_s between the snow and a snow sleigh is 0.2 or less.

Snow-Removing Resistance

The snow-removing resistance is composed of the resistance required for cutting the snow and the reaction force due to the work required to accelerate the disaggregated snow particles. Because these 2 actions are continuously and simultaneously carried out, it is difficult to separate them, and in the test both are measured together. However, at least theoretically, the two should be clearly separated. In another test series performed at the same time, the snow-cutting resistance of a knife-shaped cutting edge was obtained by using models. The results show that cutting resistance increases proportionately to the increase of cutting speed, and a cutting resistance of 0.7 kg/cm of cutting edge length was found at a speed of 18 km/hr. Although this value is considerable with a plow whose effective cutting width is 250 cm, it is necessary to reflect that the snow used in the cutting test was harder than that used in the plow test.

The snow hitting the plow moving at a high speed is accelerated as it passes over the plow surface and is thrown from the plow. The energy required for its acceleration comes from the reaction force of the plow and its speed. Therefore, the resistance for acceleration constitutes, among all resistances, the sole useful force. Snow particles fly up in the air by the energy of motion that they possess when leaving the plow and then fall on the ground; the distance of movement is influenced not only by the speed but by the direction as well, and therefore the velocity vector should be considered in order to send snow particles flying a greater distance.

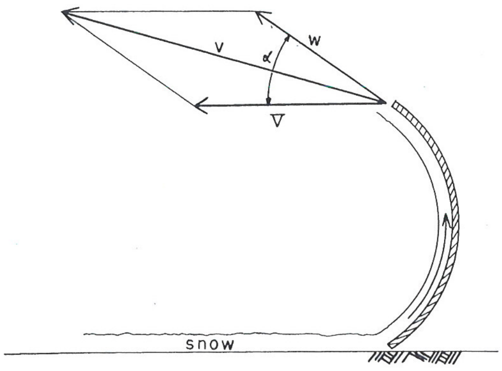


Figure 1. Velocity diagram of plowed snow.

Figure 1 shows how snow lying on the ground begins movement along the plow surface when it is cut by a plow moving at a velocity V. When it is forced along the plow surface, assuming that no crushing, cutting, or plow surface friction takes place, the relative velocity of snow particle and plow becomes equal to plow velocity V. Generally speaking, considering the lowering of velocity, the relative velocity of the snow particle w to the plow at the instant of leaving the plow is

$$\frac{w^2}{2g} = \frac{V^2}{2g} - \frac{V^2}{2g}\epsilon \tag{3}$$

where

V = velocity of plow;
g = acceleration of gravity; and
ϵ = coefficient expressing the loss in velocity energy.

Because the velocity v of snow particles against the ground is the combination of V and w,

$$v^2 = 2V^2\left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right) \tag{4}$$

where α is the snow throw-out angle formed by truck direction and plow blade.

When the density of snow on the ground is taken as γ, a cross-sectional area of snow removed as S, and the reaction force of the plow as F_O for a snow mass of $(\gamma S/g)V$ per unit of time accelerated from rest, then

$$F_O V = \frac{\gamma S}{2g} V v^2 = \frac{\gamma S}{g} V^3 \left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right)$$

$$F_O = \frac{\gamma S V^2}{g}\left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right) \tag{5}$$

In the present study, allowance is made in Eq. 3 for energy loss expressed as $V^2\epsilon/2g$, while in Eq. 5 the energy loss is excluded; but this loss is caused by plow surface and therefore, in the force R_p, which is the force exerted by the truck on the plow, it is necessary to make allowance for this loss. The assumption here is that this loss is not caused by the plow surface but all is taken outside as the kinetic energy of snow, as $\epsilon = 0$. If the reactionary force of the plow then is taken as F_p, Eq. 5 will be

$$F_p = \frac{\gamma S V^2}{g}(1 + \cos\alpha) \tag{6}$$

F_p plus the snow-cutting reaction represents the value of snow-removing resistance R_p.

The sum of the running resistance R_r of the truck, sliding resistance R_s of the plow, and the snow-removing resistance R_p is the resistance suffered while in operation. Accordingly, it is expressed as the square of truck speed, and the horsepower required for removing snow is the cube of truck speed.

Snow-Removing Efficiency

The power efficiency of removing snow is obtained from the ratio of the work done to snow to the power applied. Therefore, various kinds of efficiency may be considered according to the way of assigning these values, but, in the present case, plow efficiency η_p indicating acceleration of snow in the plow and snow-removing efficiency η_r giving the distance of cast are considered.

Plow efficiency η_p is

$$\eta_p = \frac{F_O}{R_p} \tag{7}$$

For F_o the value expressed in Eq. 5 is used, while for R_p the measured value is used. There are many difficulties in obtaining the coefficient expressing energy loss in Eq. 5. As shown in Eq. 3, ϵ is the value obtained by measuring the velocity w of snow flying out from the plow; w has not yet been measured, despite the numerous attempts so far made. For this reason, instead of Eq. 7, the following formula in which $\epsilon = 0$ is used:

$$\eta_p' = \frac{F_p}{R_p}$$

The snow-removing efficiency η_r in which the snow-casting distance L is considered may be obtained in the following way. The snow-casting distance L_o at initial velocity V_o and horizontal angle β is

$$L_o = \frac{V_o^2}{g} \sin 2\beta \qquad (8)$$

The plow reaction force F_o, which is necessary for accelerating the snow at initial velocity V_o, is (from Eq. 6)

$$F_o = \frac{\gamma S}{2g} V_o^2 \quad (1 + \cos \alpha)$$

Accordingly,

$$L_o = \frac{2F_o \sin 2\beta}{\gamma S \ (1 + \cos \alpha)} \qquad (9)$$

When actual snow-casting distance is assumed to be L,

$$\eta_r = \frac{L}{L_o} = \frac{L \ \gamma S \ (1 + \cos \alpha)}{2F_o \sin 2\beta} \qquad (10)$$

Measuring snow-casting distance L is difficult as compared with measuring the distance casting by a rotary snowplow, owing to the fact that the direction of snow throwing does not form a right angle with respect to the direction of progress, and furthermore the snow thrown is scattered over a wide area. Accordingly, η_r has large errors and poor practical use.

Snow-Removing Performance Rate

The performance of snow-removing equipment is ascertained by giving a few practical numerical examples.

The ton/hr and m^3/hr, which represent the amount of snow removed per hour in weight (ton) and volume (m^3), are often used in the case of rotary snowplows. The ton/hr is a value showing power limitation, while m^3/hr shows volume limitation.

The value called the relative snow-removing resistance is useful for indicating performance. This is given by $R_p/\gamma S$ (in which R_p is the reaction force acting on the snowplow, S is the cross section of snow removed, and γ is the density of snow) and is the ratio of plow reaction force against snow weight per unit of snow-removing length. Now, by ignoring the cutting resistance of snow and taking $R_p = F_p$ from Eq. 6,

$$\frac{R_p}{\gamma S} = \frac{V^2}{g} \ (1 + \cos \alpha) \qquad (11)$$

This value has the dimension of length, which is presumed to be related to the distance of snow-throwing. Accordingly, when 2 or more relative snow-removing resistances are compared, it is necessary to consider working speed V as an index.

As a similar method of representation, there is ton-hp/hr, whose value is often used in the case of rotary snowplows and is the value obtained by dividing the weight of snow removed per hour (ton/hr) by the power (hp) required for removing the snow. Because this value also has the dimension of length, it is necessary to take vehicle speed as an index.

TABLE 3

SLIDING RESISTANCE OF PLOW

Test Location	Coefficient of Sliding Resistance	Sliding Resistance (kg)
Nagaoka (Concrete)	0.47	188
Aomori (Asphalt)	0.39	161
Mean	0.41	167

RESULTS

Truck Running Resistance

Running resistance of the truck with the plow clear of the ground, all tires chained, and all wheels driven, on thin hard-packed snow on a paved road is obtained from the following equation:

$$R_r = W_T (0.00123V + 0.050) \qquad (12)$$

where

R_r = running resistance of truck (kg);
W_T = weight of truck (with plow 9,520 kg); and
V = truck speed (km/hr).

This value is somewhat larger than values for other vehicles; the difference of 30 percent or more depends on the type of test truck. Therefore, it is necessary to obtain data from many types of trucks.

Sliding Resistance of Plow

Before the snow-removing test was started, the sliding resistance of the plow was measured by making the plow slide on the snowless section that had been cleared during the previous test. Small differences in road surface conditions greatly affect the sliding resistance of the plow and make large measurement variations. However, after an analysis of variance was made, the only significant factor found was the kind of pavement; no significance due to speed and type of plow was found. Values obtained for the coefficient of plow sliding resistance μ_s and sliding resistance R_s are given in Table 3. The plows used were Types A and C.

Snow-Removing Resistance

Because snow-removing resistance R_p is affected by cross-sectional area of snow removed S and snow density γ, the relative snow-removing resistance $R_p/\gamma S$ given in Eq. 11 is employed to facilitate the comparison of values under various conditions. In the 1965-1966 winter test, the results shown in Figure 2 were obtained by using the Type B plow. Measurement was carried out at relatively low speed. Here relative snow-removing resistance $R_p/\gamma S$ is plotted against snow-removing speed V. From this it has been proved that the relative snow-removing resistance attains a minimum value at velocity of approximately 12 km/hr. According to the analysis of high-speed 16-mm film made at each velocity, the snow is pushed sideways and rolls along the lower part of plow whenever the truck speed is 12 km/hr or less. When the speed exceeds 12 km/hr, snow rises up along the plow surface and flows outward. Because more energy is required for rolling the snow sideways than for making it flow, the relative snow-removing resistance increases as truck speed drops below 12 km/hr. This velocity

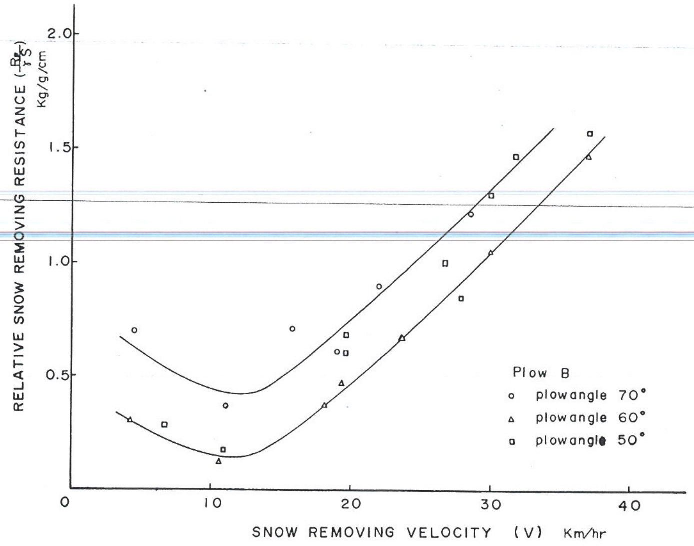


Figure 2. Relationship between velocity and resistance of snow removal.

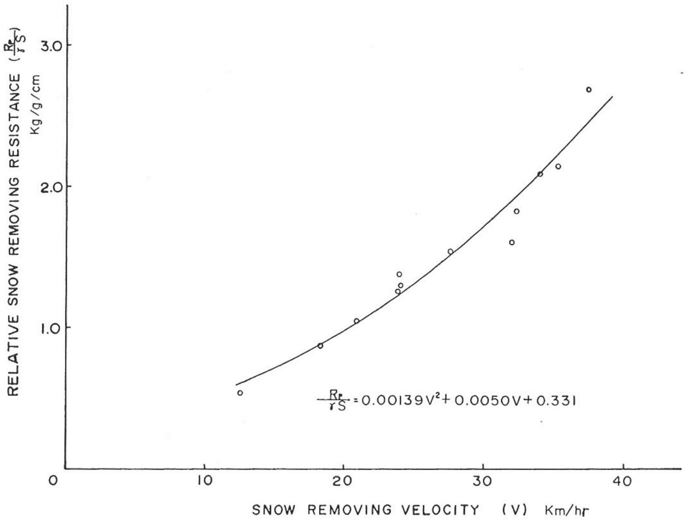


Figure 3. Relationship between snow-removing velocity and resistance of plow Type A.

limit is caused by snow rising up along the plow surface to a certain extent (30 to 50 cm) according to the truck speed.

Data for truck speeds of 12 km/hr or less were not obtained in the 1966-1967 winter tests.

Figures 3 and 4 show the relative snow-removing resistances of Type A and Type C plows plotted against vehicle velocity. The regression equations for these are

$$\frac{R_p}{\gamma S} = 0.00139V^2 + 0.0050V + 0.331 \qquad (13)$$

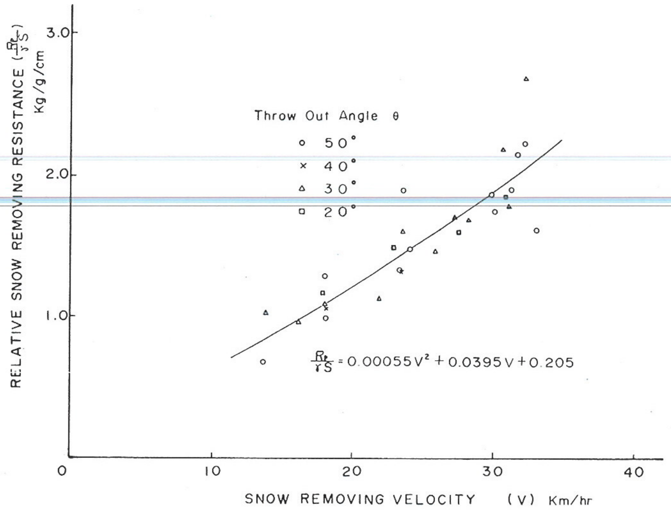


Figure 4. Relationship between snow-removing velocity and resistance of plow Type C.

for Type A plow, and

$$\frac{R_p}{\gamma S} = 0.00055V^2 + 0.0395V + 0.205 \tag{14}$$

for Type C plow, where

R_p = snow-removing resistance of plow (kg);
γ = snow density (g/cm^3);
S = cross-sectional area of removed snow (cm^2); and
V = working speed of truck (km/hr).

The value of Eq. 13 was the least when vehicle velocity was in the 12 to 40 km/hr range, which shows that the plow with the conical curved face is superior to the plow with the cylindrical curved face. Also, Type C plow tests were made at different angles.

The Necessary Truck Driving Force

The driving force required by the plow consists of truck running resistance R_r, plow sliding resistance R_s, and plow snow-removing resistance R_p, all put together. From Eqs. 12 and 13 and for Type A plow,

$$\begin{aligned} F_T &= R_r + R_s + R_p \\ &= W_T\,(0.00123V + 0.050) + 0.41\,W_p \\ &\quad + \gamma S\,(0.00139V^2 + 0.0050V + 0.331) \end{aligned} \tag{15}$$

Now, on the assumption that the truck deadweight W_T is 8,900 kg, plow weight W_p is 450 kg, snow density γ is 0.1 g/cm^3, and snow-removing cross section S is 30 cm × 300 cm = 9,000 cm^2, the driving force F_T (kg) of the truck at a vehicle speed of V (km/hr) will be

$$F_T = 1.25V^2 + 15.4V + 927 \tag{16}$$

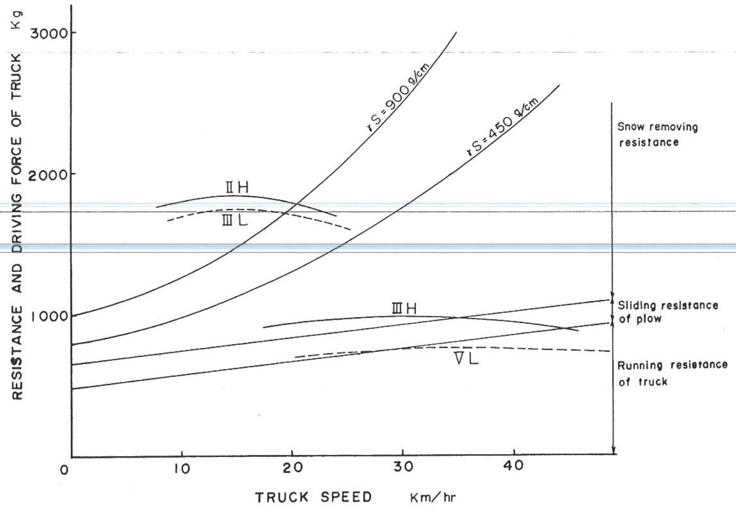


Figure 5. Resistance and driving force of snowplow truck.

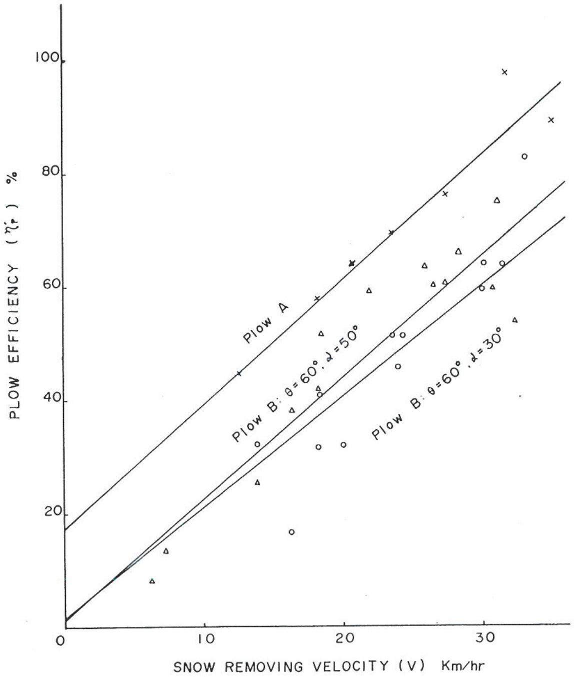


Figure 6. Plow efficiency.

This is shown in Figure 5, where the driving force of a representative truck is also given. It is clear that the running resistance of the truck itself has a large value at slow speeds. So the tractive force is calculated as 3,110 kg against the truck deadweight of 8,900 kg, which is considered satisfactory because no high acceleration or climbing resistance is included in the resistance shown in Figure 5.

The lateral snow-removing resistance of the plow, measured 960 mm ahead of the truck front axle, was one-fifth or less of that in the forward direction. When this maximum value of 744 kg is calculated as movement per 4,260 mm of truck wheel base, lateral force working on the front axle amounts to 912 kg. Theoretically, when the plowing angle is taken as θ, the lateral force F_{ps} is represented in relation to reaction force F_p in the direction of progress as

$$F_{ps} = F_p \sin \frac{\theta}{2} \qquad (17)$$

In many cases, θ is 60 deg and so F_{ps} ought to be 0.5 F_p. However, in actuality, because the snow-removing resistance F_p contains the other resistances of loss and acceleration, the ratio decreases to 0.3 or 0.4. In removing snow, one must pay attention to the fact that front wheel sideslip is likely before the driving force drops because of overloading.

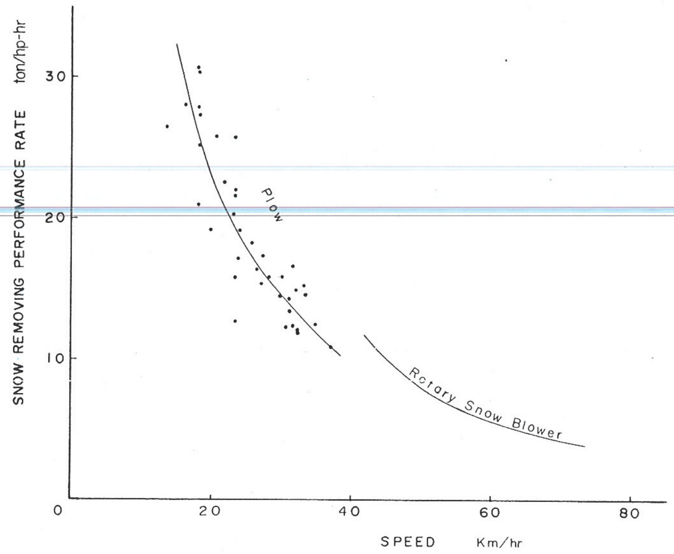


Figure 7. Snow-removing performance rate.

Snow-Removing Efficiency

The relation between snow-removing efficienty η_p' and vehicle velocity V is shown in Figure 6. η_p' clearly increases in proportion to V. This is also the case with the rotary snowblower; it is considered to be due to the fact that the snow speed is low with respect to the vehicle speed.

Rotary snowblower efficiency is 0.3 or so, but snowplow efficiency approaches 1.0 at the maximum. Therefore, it is necessary to obtain the coefficient ϵ showing energy loss and to calculate efficiency by means of η_p in Eq. 7. In Figure 6, the effect of plow throw-out angle α versus η_p' is observed. Actual measurements of snowcasting have shown that snow moves more in the direction of truck progress than in the direction tangent to the plow surface.

Snow-Removing Performance Rate

Snow-removing performance rate in tons-hp/hr plotted against truck speed V is shown in Figure 7. The curve is a hyperbola. Test results for a rotary snowblower are also shown. The speed in this case is the peripheral speed of the blower. Although the velocity range is wide, it has been proved that the snow-removing performance rate of the snowplow is inferior to that of a rotary snowblower.

ACKNOWLEDGMENT

Appreciation is expressed to the Institute of Snow and Ice Studies, which cooperated with us in carrying out these tests, and to research engineer Shigeyoshi Sawada, who aided us in the difficult tests.

Plow Clean Without Scraping

C. J. Posey

Snow is most commonly removed from highways by a plow mounted at an angle on the front of a heavy truck. If the truck moves fast enough, the snow is thrown well to the side; otherwise, it is pushed up into a ridge. At night a shower of sparks can often be seen as the blade scrapes the pavement. This wears the blade as well as the concrete and the reflective paint of traffic stripes. Where it does not contact the pavement, the blade may leave a hard-packed slippery skin of snow. Scraping can be avoided and at the same time the snow removed completely by directing a thin sheet of high-velocity air at the pavement from under the blade. The air is intended not to blow the snow off the road but to lift it a few inches off the surface so that the plow can shove it off in the usual manner.

Computations show that a turbocompressor would be required for a full-size installation. None could be obtained for use during the past winter, therefore snow-removal efficiency tests were made with a jet 6 in. long. Wet and dry snow could be completely removed from pavement and grassed areas, but not wet snow that had frozen to the pavement. It is concluded that full-scale designs should be developed and tested.

The method most commonly used in southern New England for removing snow from highways is to mount a plow with heavy steel blade and cylindrical or conical moldboard at an angle on the front of a heavy truck. If the truck is moving fast enough, the snow is thrown well to the side; otherwise, it is pushed up into a ridge. At night a shower of sparks can often be seen as the blade scrapes the pavement. This wears the blade as well as the pavement and the reflective paint of traffic stripes. Where the blade does not contact the pavement, it may leave a hard-packed slippery skin of snow. This scraping can be avoided.

A thin sheet of air directed forward under the bottom edge of the plow with sufficient velocity will lift the snow or compress its bottom layers enough so that the moldboard can push it all aside. Preliminary computations assuming different air pressures and thicknesses indicated that the air jet should issue from a slot 0.02 in. wide, and that the pressure behind the slot might vary from 2 to 5 psi. For a slot 130 in. long, computations yield the results given in Table 1.

On the assumption that 10 percent of the power of the jet is utilized in lifting 50 pounds of snow 0.20 ft. for every foot of forward motion, the theoretical maximum plow speed in clearing a 10-ft lane is 17 mph when the pressure is 2 psi, and 78 mph when the pressure is 5 psi. An evaluation based on momentum may be more realistic. If the air jet is turned from a 45-deg downward-forward angle to, say, a 75-deg upward angle, measured from the backward horizontal, the horizontal component of its momentum will be (sin 45 deg - cos 15 deg) = 0.96 times the values given in Table 1. The bottom layer of snow "approaches" with the velocity of the plow, and is turned through an angle of 180 - 75 = 105 deg. If it weighs 0.5 lb/sq ft, its relative momentum of approach is $(0.5V/32.2)V = 0.0155V^2$, where V is the plow speed in ft/sec. Because it leaves with a slight rearward horizontal component, the horizontal component of the change of momentum is $(1 - \sin 15\text{ deg})(0.0155V^2) = 0.0115V^2$. If this is equated to 0.96 times the tabulated values, the plow speed turns out to be 21 mph for 2 psi pressure and 32 mph for 5 psi pressure. Although neither of these simple analyses can be expected to represent such a complicated phenomenon very well, the results give some idea of the possibilities. Apparently the compressor will have to supply air in the range of 500 to 1,000 cu ft/min, but the pressures need not be high. With supply lines

TABLE 1

AIR THROUGH A 0.02- BY 130-IN. SLOT

Pressure (psi)	Velocity (mph)	Volume (cu ft/min)	Weight (lb/min)	Horsepower	Momentum (lb to stop)
2	330	520	42	5	10.3
5	520	820	66	21	26.0

of adequate size, 20 psi will do. The type of compressor used for operating jackhammers and air tools supplies a much smaller quantity of air at higher pressures, 80 to 100 psi or more, and is not satisfactory for our purpose. Compressors with the right capacities are available on the market, however. They can be driven by a gas turbine or by the exhaust gases of a diesel or other internal combustion engine. First developed to replace the more expensive gear-driven superchargers, "turbochargers" are coming into common use on the highest powered diesel trucks.

Because no turbine-driven compressors were available for this investigation, which has had no budgetary allocation, experiments to test the effectiveness of the air jet had to be on a small scale (Fig. 1). A slot 0.02 in. wide by 6 in. long was cut in the bottom of a copper pipe 1 in. wide and 8 in. long, to the middle of which a 1-in. by 4-ft pipe fed air brought by a 1-in. diameter pressure hose from a 40 cu ft heavy pressure tank supplied by a large stationary piston-type compressor. A valve permitted bleeding air through the desired range of air pressures desired, as measured by a pressure gage 2 in. below the valve. The are pressure at the slot was thus slightly below the pressure shown on the gage. The range was limited by the length of hose, which permitted operation only a few feet outside the northeast overhead door of the Mechanical Engineering Laboratory at the University of Connecticut, Storrs.

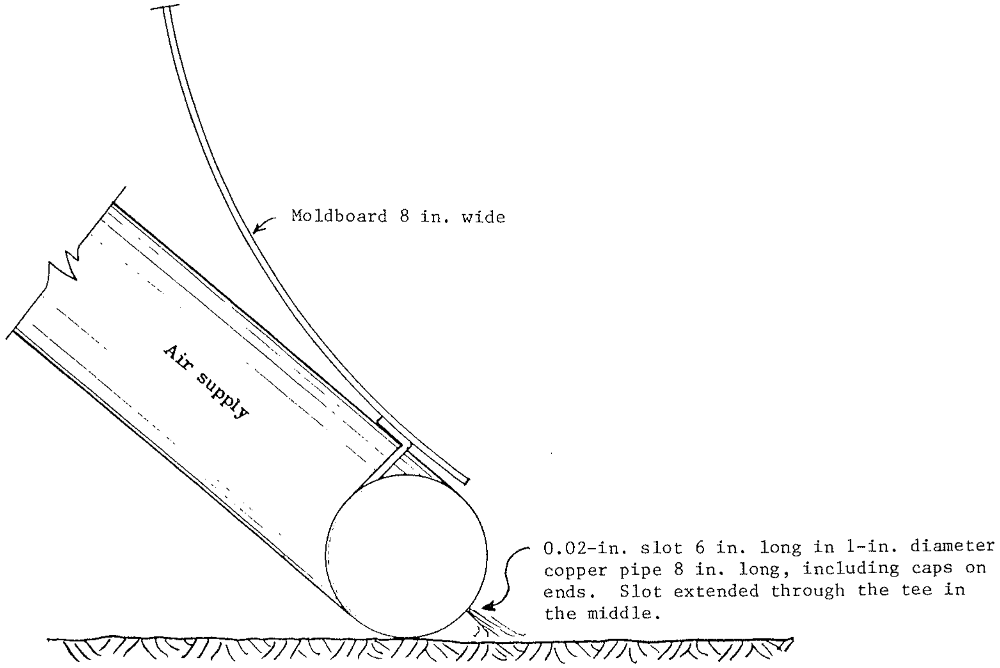


Figure 1. Model apparatus used in the tests. For full-scale installation on a plow, the pipe with the jet should be behind the moldboard and slightly farther from the ground. It seems most likely that it should be in sections about 2 ft long, each with ample-sized air supply connections.

TEST RESULTS

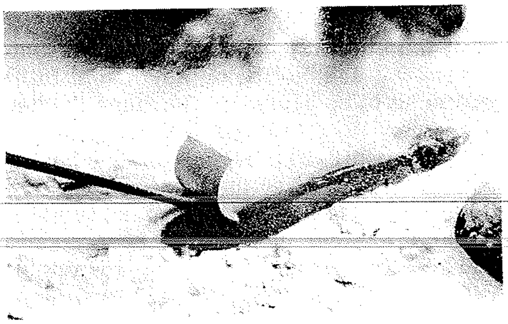


Figure 2. Operation of model apparatus in dry snow.

In addition to the limitations of the apparatus described, the tests had to wait for snows, which were not frequent in Storrs this winter. The first snow was about 6 in. deep and was followed by rain so that the bottom inch of snow was saturated. When this snow came, the apparatus was not complete, for the initial attempt at building it had produced a rough slot about 0.06 in. wide. With 2 psi pressure through this wide slot, not only was the snow lifted off the pavement, but the pavement was actually dried, and where it was cracked, pieces were blown away. The weather turned cold shortly and the saturated snow froze. The jet was then unable to clear the pavement, but it would lift the crust that had formed on the top of the snow and clean the loose snow down to that which was frozen hard.

By the time the ice had melted off and a dry 4-in. snow had fallen on bare ground, a new pipe with 0.02-in. slot had been made. Its operation is shown in Figure 2. It also cleared snow from the grass at the edge of the pavement (Fig. 3). Finally, a wet snowfall, again about 4 in. deep, was cleared as shown in Figure 4.

On Easter Sunday, Storrs had a snowfall of 7 to 9 in. Snowplows used on the local roads scrape with the blade sliding on the pavement, without support from shoes or casters, so that ordinarily much of the surface is scraped clean. The roads had been plowed before 7:00 Monday morning, but for some reason the snow had formed a crust in contact with the pavement. This crust had not been removed anywhere along the roads leading to the campus. The air jet, however, was able to remove the full depth of snow and the crust in one pass, with the pressure of 5 psi. The sun shining on the roads soon melted the frost left by the plows.

Figure 3. Snow removed from grass at edge of pavement.

Figure 4. Four inches of wet snow cleared.

POSSIBLE FUTURE DEVELOPMENTS

It is believed that these tests, modest as they may be, provide justification for developing and testing the method at full scale. The present design of the road plow will need to be changed. Perhaps the heavy carbide bar can be eliminated. It may be necessary to add wheels with tires to hold the moldboard the desired distance above the pavement. The suggestion has been made that diesel trucks equipped with turbochargers could have the compressed air fed to the jet instead of to their intake manifolds. (Use of the turbochargers is not essential for the diesel engine, but it is questionable whether the turbocharger would produce enough air with the diesel not developing full power, because this is the running condition for which the turbochargers were developed.) More likely, the gas turbine compressor will operate separately, mounted on the truck.

Many variables need to be investigated. It seems that the method should be most useful in removing snowfalls in the range of a few inches to a foot or more. With all snow removed from the pavement and shoulders, so that thawing and subsequent freezing of sheet runoff on the pavement become a rarity, it should seldom be necessary to use sand and salt.

Informal Discussion

D. L. Richardson

When you run the model at 20 psi do you achieve sonic flow through the slot?

C. J. Posey

We never went past 5 psi; I guess I did not mention it in the paper, but in the first model the slot was 0.06 in. wide, which is wider than desirable. When we applied 5 psi pressure, we not only cleared the snow, but where the asphalt pavement was a little cracked we began tearing out pieces of the pavement. So we could see that a 0.06-in. slot was too wide.

M. E. Volz

I do not see why you have a problem with compressed air because there are many available sources for the volume and pressure you need that are very simple, lightweight, and easy to operate. Have you thought about the small auxiliary power units used on airplanes? They are capable of developing up to 40 lb of air with a volumetric capacity in the thousands of cu ft/min. Do you have any idea of how many cubic feet of air at the pressures you are talking about that you would need for a full-width plow, say 16 ft?

Posey

Up to 800 to 1,000 cu ft/min at 5 psi.

Volz

How far from the pavement would you be able to discharge this air? In other words, what is the elevation of the plow above the concrete?

Posey

We used a little over ½ in., but this needs to be looked into. I would like to have your comments on the availability of these units.

Volz

Would you anticipate that the slot would be self-cleaning?

Posey

I think it would be.

Volz

What is the angle of discharge with respect to the surface?

Posey

About 45 deg forward.

Volz

Then we run into the problem of how the forward speed would affect the data you have so far, because you indicated that you pushed it by hand in your tests.

Posey

It seemed to me that, with a velocity of 330 mph, a relative velocity of 20 to 30 mph on a pavement would not make much difference.

Volz

I will be glad to talk to you about finding a source of air for your gadget. This bears looking into further. I think you have at least pointed the way to a solution to a problem that more and more people are going to have. We have it in the airline business today, but highway departments are going to have it very shortly. The problem is in-runway or in-highway lighting. Conventional plowing methods cause considerable damage to these lights. If something like this were available and could be run on rubber tires far enough above the pavement to avoid the lights, one of the very severe problems we have today would be solved.

Posey

For 10 percent efficiency, I estimate it will take 21 hp for a 10-ft blade. It could not be run off the main engine of the truck because of the rpm from the truck engine. The truck's engine would have to be geared up tremendously to run the thing. I think it would have to be a turbocharger. We could not see how far in front of the blade the air removed the snow. We had no wheels on it to hold it up, so we held it above the ground by hand.

David Minsk

I think there is little doubt that compressed air will be very effective with dry, low-density snow; really you are just blowing feathers. But the question arises, how effective will it be with wet, high-density snow or traffic-compacted snow? Did you make any comparison tests with wet snow with the air and without it?

Posey

With the air, it took care of the slush. I am sure the air can lift this up; but I do not know about hard-packed snow or ice.

A. G. Clary

The FAA has done a study with air for aircraft wheels to eliminate the hydroplaning phenomenon. Of course, this has tremendous potential if we can raise it enough to get it over the raised reflector buttons on highways. Many highway organizations are using caster wheels and shoes to hold the blade above the pavement, so this is no problem.

Posey

I am told that the caster wheels and shoes wear very badly.

Clary

There are heavy-duty casters on the market that are effective.

Engineering Studies for Snow Removal

E. C. Bain

Changes in snow-removal methods will occur when snow removal is fully recognized as an engineering problem and sufficient engineering studies are made. Because adequate information and data are not available, the design and manufacture of snow-removal equipment has changed very little since the 1930's. Some of the needed engineering studies discussed in this paper are (a) advantages of snow-throwing over snowplowing, especially in preventing snowbanks or snow traps from accumulating along highways; (b) relationships among design of equipment, speed of vehicle, amount of snow, and distances snow can be thrown; and (c) safety features required on snow-throwing equipment operated in the 20 to 30 mph range.

In the 1920's I lived in a rural district in a heavy snowfall area in eastern Canada where our Model T Ford had to be put up on blocks from December to April because of snow-blocked roads. Then we had to wait another month in the spring after the snow had gone for the roads to dry up. This, as you may appreciate, created great hardships on a boy then in his teens. Perhaps those hardships led to my continued interest in the snow-removal problem. In many areas snow removal did not start until the late 1920's and early 1930's. Following my graduation with an engineering degree, I furthered my studies of machine design and found myself during the war, from 1940-45, responsible for snow removal and winter maintenance for the Royal Canadian Air Force on airports across Canada and Newfoundland. During this period I made many visits to the United States as aviation engineers had a very close working arrangement.

Following the war I stayed in the snow-removal field and became manager of Walter Motor Trucks of Canada. It became apparent to me at an early date that while truck design had advanced rapidly, particularly with the high-horsepower engines that were becoming available, attachments for large trucks were changing very little except for the V-plow. Therefore, in 1954 I started experimenting and began designing attachments for high-horsepower trucks. I have been most pleased with the results and can report we now have 4 entirely different attachments for these trucks that have proved most successful.

The reason for this resume is to indicate that over the past 40 years many of these gray hairs I have accumulated can partly be attributed to snow-removal problems. During these years I have attended many snow-removal symposiums, and I was always somewhat amazed and annoyed that the snow-removal problem never seemed to be approached from an engineering standpoint. In fact, I was beginning to believe that no one shared my opinion until I heard David Minsk give a paper to the AAAE International Aviation Snow Symposium in 1967 in which he stated: "For one thing, no engineering study has been made in the United States of the material being handled to provide a sound basis for equipment development." I have rechecked recently with Mr. Minsk, and he confirms that this is equally true today in the United States, and I know it is for Canada because I have just completed an examination of material in technical libraries, including the National Research Council library.

In an age of such colossal engineering achievement, it is astonishing that more engineering information on snow methods and techniques is not available. This whole problem becomes more ridiculous when we consider that we can get a man to the moon and back, yet we cannot get him from one town to the next after a moderate snowstorm—no wonder we often have a state of emergency declared.

ENGINEERING STUDIES FOR SNOW REMOVAL

Because engineering data are not available, the design of a great deal of snow-removal equipment has changed very little since the 1930's, even though high-horsepower, high-torque engines are now available for trucks. I feel very strongly that adequate engineering studies would show many things in terms of economic factors, new techniques and methods, and more correct selection of horsepower requirements; needless to say, they would bring advancement in the design of snow-removal equipment. In this paper I am confining my remarks mainly to roads, highways, and airport areas where it is possible to use high-speed snow-removal equipment.

Snowbanks and Snow Traps

Our most serious and costly problem is snowbanks or snow traps along roads and highways. This problem has been most successfully attacked by highway planners, designers, and construction engineers. They have done a tremendous design job and eliminated many snow traps, but much is still needed from the mechanical standpoint. It was recognized at an early date that snowbanks and snow traps can accumulate great tonnages of snow, particularly when there are snowdrifting conditions. For example, 1 ft of snowbank can trap 1,000 tons of snow per mile, and 10 ft of snowbank can trap 10,000 tons of snow per mile. These large tonnages take enormous effort to remove no matter what type of equipment is used. Therefore, some method of mechanical means must be used by the maintenance engineer to prevent these snowbanks from building up. Slow-moving equipment that pushes or plows snow to the side of the road in an area where speed can be maintained could be the worst action. In fact, the V-plow is the most efficient attachment for the opening of snow-blocked roads, while at the same time it can be classed as the most effective piece of equipment yet devised for the building of snowbanks when operated at slow speed.

Classification of Snow Removal Methods

Every piece of snow-removal equipment should be valued and classified for the type of work it is expected to do. A suggested division is as follows:

No.	Type of Work	Type of Equipment
1	Snow-dozing	Very slow-moving equipment
2	Snowplowing	Slow-moving equipment
3	Snow-throwing	Fast-moving equipment
4	Snowblowing	Rotaries of various types

There appears to be the greatest confusion between snowplowing and snow-throwing equipment. In fact, too little is known about the snow-throwing possibilities. I was very pleased to hear that this is receiving some attention in Japan.

At slow speeds snow is pushed or plowed, but at the faster speeds of 20 to 30 mph it is thrown. With high-horsepower, high-torque trucks, it can be thrown in very large tonnages. Properly designed snow-throwing equipment powered with large engines has been used most successfully for years by the railroads. Any railway engineer will tell you that they never plow snow but that they operate at 30 to 35 mph speeds and throw snow in large tonnages. They have always used momentum and high-horsepower engines.

To substantiate my opinions and observations I find it necessary to present data on attachments that we have compiled for high-horsepower, high-torque powered trucks, because other information does not appear to be available in any technical library. In presenting my data, my chief concern is that it not be interpreted as a sales talk. I can assure you that the data used were compiled by a government source, and I was not aware of the results until many months after they were collected.

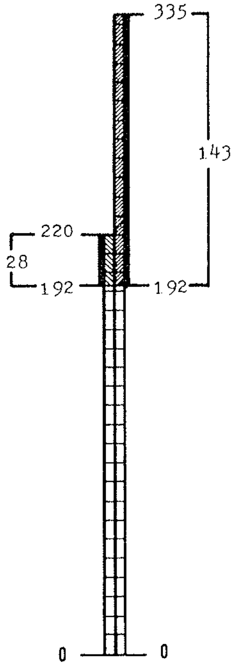
The question may be asked, What is new in the information we have collected compared to the snow-throwing methods we have used for years? I agree that for very light snow the snow-throwing method has been used very successfully, but for moderate or heavy snow in most cases it has not. The reason is that there is not sufficient power and torque available in most truck engines to maintain snow-throwing speeds of 20 to 30 mph. From 1930 through 1950, engines of sufficient size were not available, but that is not the case in the 1960's. During the period when snow-removal demands increased, the trend was to increase the number of units rather than to get more efficient units.

Figure 1 shows the comparison between 2 identically equipped trucks, one powered with a 220-hp engine and the other with a 335-hp engine. This figure gives some idea of the snow-throwing capacity of each unit in the 20 to 30 mph speed range. The truck with the 335-hp engine has 410 percent more horsepower available than the 220-hp truck.

If we accept the accuracy of these figures, then how can it be possible to throw snow in large tonnages with low-torque engines? Most gasoline engines used in snowplow trucks have between 350 and 500 ft-lb of torque at 2,800 rpm. Compare this to the 220-hp diesel with 606 ft-lb at 1,600 rpm. Even with the 220-hp diesel, the 28 hp available for snow-throwing is about the same as we now find in a modern snowmobile. The difference in price of the engine in a truck powered with the 220 or 335 hp is less than $1,000; therefore cost is not the deciding factor.

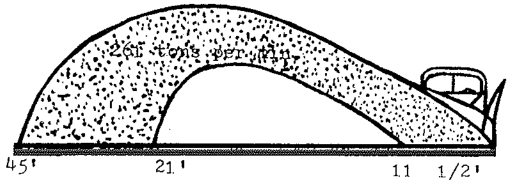
Figure 2 shows that tonnage up to 261 tons/min was thrown at a distance of up to 45 ft at 32 mph when a 300-hp, 700 ft-lb torque engine was used in a truck with a new design in snow-throwing attachments. In the second test, 266 tons/min was thrown 29 ft at 22 mph.

In both tests it was indicated that sufficient horsepower was still not available, because the deciding point should have been where the snow-thrower pushes sideways out of the snow and this point was never reached. It was calculated that, to maintain 25 mph, over 400 hp would be required. Such engines have recently become more popular, and the possibilities in this field are tremendous. However, very careful consideration has to be given to snow-throwing attachment design, particularly one that will give a



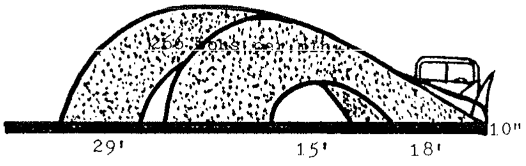
Item	220 hp 606 ft-lb Torque 1,600 rpm	335 hp 865 ft-lb Torque 1,400 rpm
Accessories and hydraulic losses	-32	-32
Drive-line losses	-40	-40
Rolling resistance 40,000 GVW at 25 mph	-53	-53
Cutting-edge resistance	-67	-67
Total losses	-192	-192
Available net horsepower at 25 mph for throwing snow		
on 0 deg grade	28	143
on 2 deg grade	0	90

Figure 1. Comparison of 2 identically equipped trucks with 335- and 220-hp engines.



frontal area of snow, 8 sq ft
speed, 32 mph
distance traveled, 2,816 ft/min
snow displaced, 22,528 cu ft/min
or 261 ton/min

Snow very wet, 27 lb/cu ft, 7 in. deep



frontal area of snow, 15 cu ft
speed, 22 mph
distance traveled, 1,936 ft/min
snow displaced, 29,070 cu ft/min
or 266 ton/min

Snow very wet, 33 lb/cu ft, 10 in. deep

Figure 2. Snow-throwing in large amounts (extra tonnages due to advantage of right moldboard).

wider swath, such as wing or side moldboards. They must be fitted with safety features that enable rapid folding. With properly designed snow-throwing attachments on high-horsepower, high-torque trucks there would be greater efficiency, more roads open, and better service to the public.

Economics

From the standpoint of economics, I believe the amount saved would be in the millions. An analogy can be made between snow equipment and airport crash trucks because both are emergency equipment. The users of crash trucks have recognized that it takes 3 men per 8-hour shift or 9 men for 24 hours and 3 extra men to cover the 40-hour week, a total crew of 12 to man 1,000 gallons. The same number is required to man a 3,000-gal unit. Therefore, when a 3,000-gal unit was used instead of three 1,000-gal units, savings (based on $10,000 per man and two 12-man crews) amounted to $240,000 per year. Over a 10-year period, this would be $2,400,000. Although the savings would not be as great with snow-removal equipment, which is used seasonally, the savings would also be colossal. Only accurate and sufficient engineering studies will indicate the course we are to follow in the future and will bring about the necessary changes in design. In fact, our present design, shapes, and angle of blades may prove to be as obsolete as the 1930 automobile.

SNOWBLOWERS AND ROTARIES

Snowblowers or rotaries do very well the job for which they were designed. They can load snow and throw snow greater distances than snow-throwing truck attachments. Unfortunately, their tonnage range is from 0 to 35 tons/min. When great distance of throw is not required, properly designed snow-throwing attachments can throw up to 260 tons/min, nearly 10 times as much. As indicated earlier there are many areas where this snow-throwing technique cannot be practiced and snow ridges or banks will be built up. Therefore, for these conditions other methods should be used to cut down and remove these snowbanks.

Safety Attachments

Safety may be one of the chief reasons why the snow-throwing method in the 20 to 30 mph range has never been fully developed. Trucks should be fitted with a safety speed wing that folds instantaneously when operated in traffic or when obstructions are encountered. Speed wings or side moldboards should be designed from the standpoint of shape, contour, and angle (a) to throw snow safely in the 20-30 mph speed range; (b) to throw snow at this speed without the chassis being swung around or off the road when obstructions are encountered; (c) to fold instantaneously should the operator need to get around obstructions; and (d) to make it unnecessary for the operator to pull out into the oncoming traffic lane when passing parked or stalled vehicles because the operator can push the control handle and the wing or moldboard will fold in.

Informal Discussion

D. L. Richardson

Do you have any complaints from your citizens when the snow winds up on their front porches?

Bain

We have quite a few of them. In one province we have to issue special instructions to move cars back 25 ft because the first time we drove into 2 cars. That did not help too much politically.

P. A. Schaerer

I am surprised to hear that some areas of the country are so backward in snow removal, and I do not want our friends from overseas to go back home with the wrong impression. I would just like to say it is not so in the west of this continent. From my knowledge of the roads in British Columbia, snowblowers are gradually being pushed out of work because plows are more powerful and can throw the snow to the side. There are plows available that plow uphill on 6 percent grades at 30 or 40 mph.

Bain

That is right. They use turbine engines. We are talking about using engines in the 350-hp range, such as Cummins 335 and GM 871. We are building a unit now with a V-12 engine, which will have 450 hp. In British Columbia, they have recognized that because of the grades they will have to go to a turbine engine to get the horsepower although it is not too economical on fuel. We are going to stick to diesels for a while yet.

David Minsk

The science of snow mechanics began in 1936, probably, at the Swiss Federal Institute for Snow and Avalanche Research. Unfortunately the work was printed in German and required the ability to read and interpret. That was not done on this continent for some time. There is an immense amount of material available on the science of snow mechanics and the properties of snow, but the engineering application of this information has not been done to any great extent. And that is the point I made, and it should be interpreted as such. Many of the tests that have been run in this country and elsewhere should have been reported in the Journal of Irreproducible Results because they did not take into consideration the properties of the material. It is available in Canada at the National Research Council, an organization with which we have very close working relations. What is required by the individual interested is the ability to read and interpret what is available to make engineering applications.

Richardson

The plow you showed plowed at one angle then reversed to another angle for use as a V-plow. Have you had much truck damage from hitting an obstruction while plowing at that speed?

Bain

That plow was built for a special use in an area where we had terrific drifing. We would go up with a one-way plow for about a mile and then strike a drift area. We could then swing the plow to a V and came back through it. We could also directionalize snow. In other words, if the snowbank was filling up on one side, we could use the plow as a dozer to doze it down. A big problem is to get the operators to use it as it is supposed to be used because some are used to the old V-plow and some are used to the one-way plow. I am not saying that this is the ultimate answer. I am saying that engineering studies will bring about, I think, quick changes in all types of equipment.

Current Research on Snow Removal and Ice Control on Roads in Japan

Raizo Tsuchiya and Motoya Inoue

This report describes various research studies relating to snow and ice on roads in Japan. Some of the results have already been applied in planning, design, maintenance, and operation of road projects. The studies deal with the following: the estimation of the effects of snow depth, topography, and vegetation on avalanche generation; the estimation of snow depth along planned routes, especially in mountainous areas where meteorological observations are not made; the classification of snow on road surfaces and the development of a highway ice information system; the space needed for roadside snow mounds and the design of that space; and the efficiency of different types of snow-removal equipment.

The Japan Islands lying from south to north have considerable differences in meteorological conditions between the south and the north. Accordingly, there is a great difference in quality of snow and ice from region to region. There are many snowbound zones where snow depth usually exceeds 2 m, and it is by no means rare that even housetops are covered.

Japan is located rather low in latitude compared with European nations, so that the surface of the earth is warmed by insolation even in winter. A thin snow or ice film covering the paved surface will likely melt during the daytime.

The large intensity of snowfall, the large amount of snowfall, the abundant insolation, the great extremes in meteorological conditions according to district, and the like constitute the characteristic features of winter weather in Japan.

SNOWBOUND AND COLD-CLIMATE REGIONS

Snow-coverage and cold-climate regions are defined by a law enacted in 1956 for securing the road traffic in cold and heavy-snow areas. A snow-coverage region is defined as the region where the annual mean of maximum snow depth in February exceeds 50 cm. The cold-climate region is the region where the annual mean of temperatures in January falls below 0 C.

Japan has an area of 369,779 km^2 of which 53 and 52 percent respectively are within these defined regions and 61 percent is within both of them. The population in the regions is 25 million.

SNOW AND ICE ON ROADS: STUDY AND COUNTERMEASURES

The history of study and control of snow and ice on roads is very young in Japan. The study and control started about 1962 except in limited areas where it started about 1940. This may be due mainly to progress in arrangement of roads about that time and a rapid increase in traffic in snowy areas as well as a bitter experience of heavy snowfall throughout Japan in January 1963.

Construction of trunk roads has been making headway in those areas, and traffic accidents continue to increase. It is, therefore, required that greater importance be placed on the study of control of snow and ice on roads in the future.

STUDIES CONDUCTED IN JAPAN

To guarantee safe winter road traffic in snowy regions is indispensable to the public welfare as well as to the sound growth of industries and economy in such areas. Snow-removal projects in those areas are expanding, and techniques employed are improving. It is desirable that effective steps be taken on the basis of general studies on the economy of snow removal from roads, the structures of highways, the properties of snow layers on roads, and snow-removal and snow-protection methods, and so on.

Economic Effects of Snow-Removal From Road

How to evaluate the economic effects of snow removal from roads has been discussed in various ways. Two methods of rating include (a) a macroscopic method that deduces the economic effects from the volume of work accomplished in terms of traffic volume multiplied by traveling time, and (b) a microscopic method that determines the effects in terms of convenience of driving and economy of traveling time due to snow removal. It has been demonstrated that snow removal has notable economic effects regardless of whether they are rated by the first or by the second method.

Geometric Design of a Highway in a Snowy Region

In mechanical snow removal, loading and hauling snow is less efficient than clearing it sideways from the roadway. Therefore, a highway should have surplus width on each side to accommodate such piles of plowed snow. Studies undertaken on this problem have proposed that a surplus width be specified suited to the snow depth on the basis of the shape and density of snow piles. Because the properties of snow differ from region to region, similar studies should be carried out separately for each region.

Properties of Snow Layer on Roads

Efficient snow removal and effective traffic control in snowy regions presuppose perfect comprehension of the properties of the snow layers on roads. Some study has proposed that, through microscopic observation, snow be classified into new snow, powder snow, granular snow, packed snow, and ice film. Further studies on the relationship between the types of snow and the slip of a tire should be conducted. Removing packed snow is particularly important to smooth traffic flow. In this connection, an easy way to clarify the properties of packed snow has been discussed. Such a method will surely help establish objective standards for snow-removal work, which has been undertaken only on the basis of past experience.

Snow-Removing Machines

Selection, combination, and arrangement of snow-removing machines are important. A method to calculate the necessary number of machines of each type was discussed, and new high-performance machines have been introduced. In making a selection, one should consider the conditions of snow and other relevant factors in the area.

Spreading Chemicals

Chemicals, mainly chlorides, are often used to prevent freezing and to melt ice and snow layers on paved surfaces. Reports on methods of using such chemicals and the results of indoor experiments and field tests were examined. New chemicals and new methods of application are expected to be developed soon.

Snow-Removal and Snow-Protection Facilities

There is a growing trend toward an increased use of snow-removing facilities installed along highways instead of mobile snow-removing machines. The installation includes a pipe system through which seawater is pumped. Figure 1 shows the construction of such a pipeline, and Figure 2 shows the system in operation. The intake of seawater and the feed pumps are shown in Figures 3 and 4. Data for designing snow-draining ditches and the practical performance of a road-heating system were also studied. However, many problems must still be solved with these methods.

Data based on model tests are available for designing and arranging snow fences. The application of these data requires that the conditions of the site be investigated.

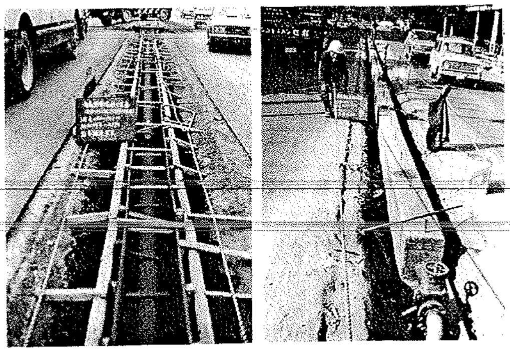


Figure 1. Pipeline being installed along centerline of road; water nozzles protrude from concrete.

Figure 2. Seawater being sprayed on street from nozzles.

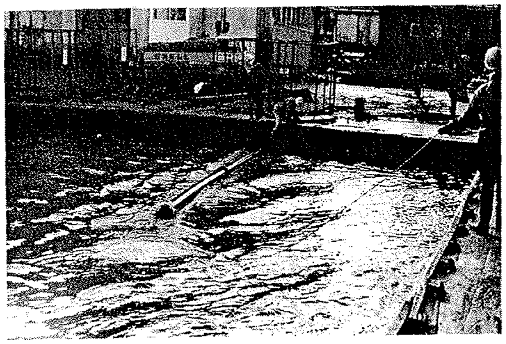


Figure 3. Intake of seawater.

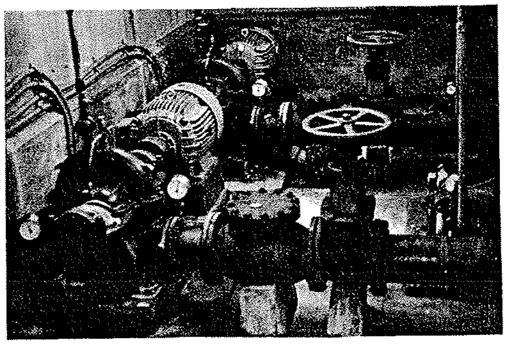


Figure 4. Feed pumps in pumphouse.

Moreover, the performances of fences already installed should be examined before other fences are installed.

There are several methods to protect road traffic from the danger of avalanches. Study has been carried out on criteria for installing facilities, characteristics of existing snowsheds, ways to estimate the probability of avalanches in a given area, ways to estimate the load of an avalanche, and ways to control avalanches such as using explosives and an avalanche gun. Some progress has been made in the research and exploration of avalanche control, but more concrete methods of application should be found to meet diversified demands arising from different traffic requirements, topographical features, and meteorological conditions in different regions.

RESEARCH ORGANIZATIONS

The leading organizations conducting snow and ice research in Japan include the Institute of Low Temperature Science, Hokkaido University, N17 jo, W7 chome, Sapporo; The Institute of Snow and Ice Studies, National Research Center for Disaster Prevention, 9,628 Motoyoshi-sho, Nagaoka, Niigata; Civil Engineering Research Institute, Hokkaido Development Bureau; Railway Technical Research Institute, Shiozawa Snow Testing Station, Japanese National Railways, 1,108-1 Shiozawa cho, Minami-Uonuma, Niigata; Public Works Research Institute, Chiba Branch, Ministry of Construction, 4-12-52, Anagawa, Chiba; and Snow and Ice Laboratory, DoroKodan Shikenjo, Japan Highway Public Corporation, 1,789, Yamazaki cho, Machida, Tokyo.

Informal Discussion

A. G. Clary

How do you keep the seawater system down the center of the street from freezing?

Inoue

The area where the water-spray system is being used is a comparatively warm district. The mean temperature is about 0 C. In the cold regions it is difficult to use this system, but most cities in Japan are in comparatively warm areas.

Clary

Use of the infrared lamp as a de-icing means here in the United States has not proved desirable because of the wind and the reflection of the snow. Is the use widespread in Japan, and is it practical there?

Inoue

In Japan the infrared system is not used very often.

M. E. Volz

I want to make a comment about infrared, because I am sure that everybody is blessed with 20-20 hindsight. We built a new hangar at a cost of about $13 million and installed an infrared heating system inside with the idea that we could de-ice airplanes very rapidly in this building by just pulling them in one side and out the other. The first airplane we pulled in sat there for 38 hours and had not lost any snow by the next day. We decided that either we could paint the tops of all our airplanes black or we could change the heating system. We did the latter.

Models for Predicting Snow-Removal Costs and Chemical Usage

Edward L. Miller

One of the objectives of a maintenance cost study by the Ohio Department of Highways is the determination of the major factors that influence maintenance costs. This paper describes several models developed by multiple-regression analysis to predict cost per lane-mile for snow and ice removal on Ohio highways. The models indicate that the 2 most significant independent variables affecting cost per lane-mile for snow and ice removal are inches of snowfall and average daily traffic. The models have been used to budget snow- and ice-removal funds by applying 30-year weather data and current ADT to compute anticipated costs.

This paper explains a method for distributing snow- and ice-control funds to the Ohio state highway system in 88 counties so that differences in route type, road mileage, traffic, and weather are taken into account. Multiple linear regression has been used to obtain mathematical models that give the relationship between cost per lane-mile, ADT, and snowfall for each of 5 route types. The method is the outgrowth of the application of multiple-regression analysis to various maintenance costs in the Ohio Maintenance Cost Study, a federal-aid highway research project now in its ninth year, undertaken in cooperation with the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

The Ohio Department of Highways carries the responsibility for maintaining rural highways on the state highway system and for Interstate highways in both urban and rural areas. Seven of the 8 largest Ohio cities maintain the Interstate highways within their corporate limits and are reimbursed by the state for such maintenance work. The state highway system comprises 18,766 centerline-miles or 38,793 lane-miles. County and township roads and highway and streets within cities are not the responsibility of the Ohio Department of Highways, nor is the Ohio Turnpike.

The state highway system is divided into 5 types of routes: Interstate, divided major highways, 2-lane major highways, auxiliary highways, and local highways. Table 1 gives the lane mileage for these 5 types by county, division, and state.

Today in the various highway departments throughout the United States 2 different approaches seems to be developing for answering the question, How much money is needed for highway maintenance? This question includes, of course, the question, How much money is needed for snow and ice control in the safe operation of highways? One approach is to inventory not only the miles of pavement but also all other elements of the highway, such as guardrail, acres of right-of-way, miles of ditch, miles of fence, and number of signs. With such an inventory, someone at the field level determines what part of the inventory needs maintenance and repair work. Optimum work methods for doing each item of work are established as are standards for the labor, equipment, and material related to each work item. From these elements a division total is generated and the various division totals are combined to reach a total for the state. In our view, the resulting planning and scheduling requirements are difficult to handle. We are using a different approach to the problem in Ohio.

The Ohio Department of Highways is composed of a central office staff and 12 field divisions. The field divisions are responsible for the construction, maintenance, and operation of state highways. In most cases, divisions consist of 6 to 8 counties (Fig. 1). Funds for maintenance are allocated by the central office to the divisions, and a uniform cost reporting system is used by all divisions. The central office processes the cost data on an IBM 360/50 computer system. By means of this system reports are produced

Figure 1. Field divisions of the Ohio Department of Highways.

that permit comparison of labor, equipment, and material costs among counties within the division and among divisions. By such comparisons, inefficient operation is made evident and is then investigated and corrected by the division management.

Table 2 gives the direct costs for the 15 highest individual work activities, listed in decreasing order of magnitude. The application of chemicals for snow and ice control is the single most costly work item in the entire list of maintenance activities. The amount will vary from year to year depending on the weather, but the item heads the list every year. For this reason there is a continuing surveillance of this activity by both central office and division management. Regression models were developed because of the magnitude of the expenditure for snow and ice control and the related effort by management to evaluate the need for such funds.

Table 3 gives by route type the average snow- and ice-control cost per lane-mile in fiscal year 1969 for the state. Figure 2 shows the large variation in mean annual

TABLE 1

HIGHWAY LANE-MILES BY DIVISION AND TYPES OF ROUTES

Division	Type 10	Type 20	Type 30	Type 40	Type 50	Total
1	193.64	224.30	660.70	1,532.14	549.06	3,159.84
2	256.16	345.60	793.66	1,383.50	363.02	3,141.94
3	292.76	600.80	887.88	1,273.14	768.92	3,823.50
4	454.06	428.96	1,028.40	1,150.12	424.58	3,486.12
5	455.36	279.04	649.50	1,295.32	768.04	3,447.26
6	369.48	382.92	882.42	1,026.22	613.10	3,274.14
7	299.60	258.68	533.30	1,720.60	746.64	3,558.82
8	770.24	395.18	975.98	1,009.64	578.54	3,729.58
9	0	466.60	646.62	1,566.90	638.36	3,318.48
10	145.76	205.88	833.74	1,671.80	890.32	3,747.50
11	192.08	132.36	714.08	1,388.46	510.50	2,937.48
12	360.30	112.22	173.42	393.14	130.18	1,169.26
Total	3,789.44	3,832.54	8,779.70	15,410.98	6,981.26	38,793.92

TABLE 2

DIRECT MAINTENANCE COSTS IN FISCAL YEAR 1969

Activity	Cost ($)
Applying chemicals for snow and ice control	5,830,440
Patching surfaces	3,264,767
Controlling vegetation, mowing	2,483,113
Maintaining aggregate shoulders	1,647,951
Maintaining ditches and paved gutters	1,242,480
Sealing and surface-treating pavement	1,063,612
Maintaining rest areas	1,035,541
Maintaining signs	836,190
Marking centerlines	740,919
Sealing cracks and joints	700,312
Picking up litter	665,580
Removing brush, trees, and stumps	643,123
Cleaning and painting bridges	620,777
Repairing bridges	542,190
Marking edge-lines	508,189

TABLE 3

DIRECT COST FOR SNOW AND ICE CONTROL IN FISCAL YEAR 1969

Type of Highway	Cost per Lane-Mile ($)	Cost per Centerline-Mile ($)
Interstate	301	1,205
Divided major	183	734
2-Lane major	128	257
Auxiliary	138	277
Local	118	236

Note: Costs are statewide mean values.

snowfall over the state. In the northeastern part of the state the annual snowfall is 100 in., whereas for most of the other areas it is only 20 or 30 in. The contours are based on U.S. Weather Bureau data for approximately 30 years. Figure 2 also shows the Interstate highways in relation to the annual showfall; the location of the Interstate highways within the counties is shown in Figure 3. The direct cost for snow and ice control on Interstate highways is $1,205 per centerline-mile, a figure much higher than that for other route types (Table 3). Most of the Interstate route mileage is located in areas of moderate snowfall. Only I-90 from Cleveland east and portions of I-71, I-77, and I-80 south of Cleveland are in the high snowfall area.

Because of the large differences in route types, mileage, mean annual snowfall, and average daily traffic, a method for distributing funds for snow and ice control was needed that would account for such differences. Multiple linear regression was used to develop mathematical models to distribute funds for snow and ice control.

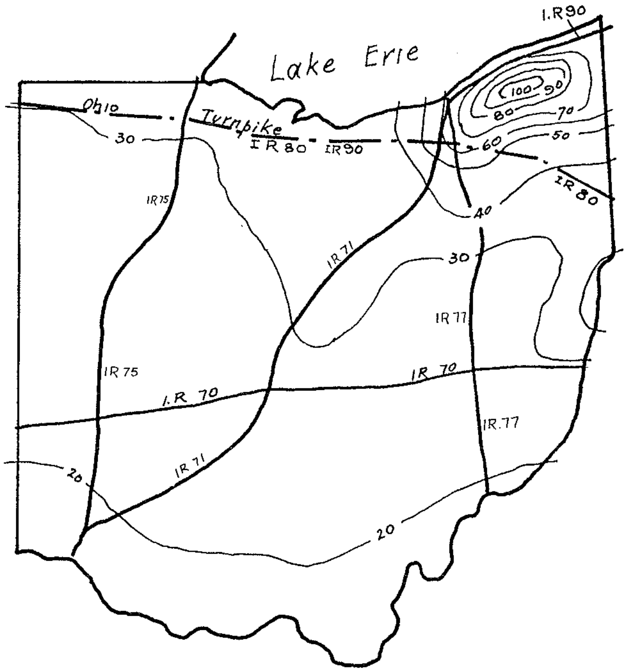


Figure 2. Annual snowfall based on 30-year mean and location of Interstate highways.

Figure 3. Location of Interstate highways within counties.

MULTIPLE REGRESSION

A computer program for multiple linear regression, available from IBM and described in its publication H20-0205-2, has been used. A few changes in input and output were made. The program is written in FORTRAIN IV and permits 99,200 observations with 15 variables and 51,200 observations with 40 variables. It computes mean values, standard deviations, correlation criteria, regression coefficients, and various confidence measures.

The t-test was used to determine whether the regression coefficient obtained for each variable was significantly different from zero. In the present case, the null hypothesis was based on the assumption that the coefficient might be zero.

The computed t-value, which is the ratio of the calculated regression coefficient to the standard error of that coefficient, was compared to a table of t-values having a 0.05 significance level for the appropriate degrees of freedom. If the computed value was larger than the table value, the hypothesis was rejected and the regression coefficient accepted as being significantly different from zero.

Like the t-test, the F-test also includes setting up a hypothesis and then calculating F on the basis that the hypothesis is true. However, where the t-test is a measure of the probability that the regression coefficient is significantly different from zero, the F-test provides a method for determining whether the ratio of the variance is larger than might be expected by chance if it had been drawn from the same population.

The University of California, Los Angeles, has developed a comprehensive battery of statistical programs for biomedical research. In order to make the major programs more readily available to the users of the IBM 360 urban transportation planning battery, the Bureau of Public Roads has included in the battery executable load modules for the 5 most frequently used BIMED programs. One of the programs, Stepwise Multiple Regression, is now on hand in the computer section of the Ohio Department of Highways, and it will be used in our future regression work.

MODELS

The models produced by multiple linear regression give the relation of direct cost (i.e., labor, equipment, and materials) to snowfall and traffic, the independent variables in the models. If

Y = cost per lane-mile (labor, equipment, and materials) for plowing snow, applying chemicals, and cleaning bridges,
X_1 = inches of snowfall, and
X_2 = average daily traffic,

then

$$Y = 7.40\,X_1 + 159.27 \qquad (1)$$

for Interstate highways (route type 10);

$$Y = 4.20\,X_1 + 0.04\,X_2 - 36.75 \qquad (2)$$

for major highways (route types 20 and 30); and

$$Y = 3.54\,X_1 + 0.05\,X_2 + 9.92 \qquad (3)$$

for auxiliary and local highways (route types 40 and 50).

The model (Eq. 1) indicates that the cost per lane-mile for Interstate highways is independent of traffic. It is believed that this is because there is not a sufficiently large variation in traffic volume on Interstate highways to make it a significant factor in varying the cost of snow and ice control. ADT was used as an independent variable in the regression for Interstate highways, and the resulting regression coefficient was not significantly different from zero.

These models were computed by using input data from the fiscal years 1967 and 1968.

Other independent variables were tried in the regression analysis and the resulting coefficients were found to be not significantly different from zero. The variables tried were as follows:

No.	Variable
1	Average temperature for the winter season
2	Number of days when temperature was 32 F or below
3	Number of days when snow fell
4	Average maximum temperature
5	Average minimum temperature
6	Number of degree days
7	Terrain (Fig. 4)

The input and output data for the 3 equations are given in Tables 4, 5, 6, 7, and 8.

INPUT DATA

The input data used to produce the models were as follows:

1. The cost per lane-mile for each route type for each county was used. Interstate highways are located within 33 counties, so the input consisted of 33 observations or sets of data. The cost used was the 2-year mean value for each county for the fiscal years 1967 and 1968.
2. Data from the U.S. Weather Bureau for 1967 and 1968 were averaged for each county.
3. Average daily traffic values for each county by route type was available from the Bureau of Planning Survey, Ohio Department of Highways.

Figure 4. Terrain of counties.

TABLE 4

REGRESSION ANALYSIS

Item	Interstate Highways (Eq. 1)		Major Highways (Eq. 2)		Auxiliary and Local Highways (Eq. 3)		
	Variable 2	Variable 4	Variable 2	Variable 4	Variable 2	Variable 3	Variable 4
Mean	34.042	411.181	33.054	244.203	33.045	1,444.657	199.641
Standard deviation	11.920	200.155	14.149	125.112	14.050	1,148.510	107.473
Correlation X versus Y	0.441		0.477		0.493	0.564	
Regression coefficient	7.400		4.196		3.541	0.050	
Standard error of regression coefficient	2.707		0.691		0.627	0.008	
Computed t-value	2.733		0.074		5.650	0.565	
Intercept	159.272		-36.748		9.915		
Multiple correlation	0.441		0.761		0.729		
Standard error of estimate	182.547		82.355		74.596		

TABLE 5

ANALYSIS OF VARIANCE FOR THE REGRESSION

Highway	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Value
Interstate (Eq. 1)	Attributable to regression	1	248,962.5	248,962.5	7.471
	Deviation from regression	31	1,033,027.4	33,323.5	
	Total	32	1,281,990.0		
Major (Eq. 2)	Attributable to regression	2	643,381.6	321,690.8	47.430
	Deviation from regression	69	467,983.4	6,782.4	
	Total	71	1,111,365.0		
Auxiliary and local (Eq. 3)	Attributable to regression	2	442,123.6	221,061.8	39.727
	Deviation from regression	70	389,515.1	5,564.5	
	Total	72	831,638.8		

TABLE 6

INPUT-OUTPUT DATA FOR INTERSTATE HIGHWAYS

County	Cost per Lane-Mile for Labor, Equipment, and Materials			Snow-fall (in.)
	Value	Estimate	Residual	
1	320.920	444.167	-123.247	38.5
2	307.810	377.568	-69.759	29.5
3	523.320	479.687	43.633	43.3
4	395.610	365.729	29.881	27.9
5	430.370	443.427	-13.057	38.4
6	774.760	487.086	287.673	44.3
7	791.570	491.526	300.043	44.9
8	829.610	444.167	385.443	38.5
9	860.550	627.684	232.865	63.3
10	239.380	295.429	-56.049	18.4
11	600.490	280.630	319.860	16.4
12	101.950	327.249	-225.299	22.7
13	363.410	512.246	-148.836	47.7
14	186.710	525.566	-338.856	49.5
15	342.800	441.207	-98.407	38.1
16	184.560	388.668	-204.108	31.0
17	370.150	432.327	-62.177	36.9
18	610.580	431.587	178.992	36.8
19	428.330	457.487	-29.157	40.3
20	352.180	373.128	-20.948	28.9
21	389.830	311.709	78.121	20.6
22	240.190	495.226	-255.036	45.4
23	408.460	399.028	9.432	32.4
24	253.570	320.589	-67.019	21.8
25	442.490	487.826	-45.237	44.4
26	168.760	374.608	-205.848	29.1
27	383.630	314.669	68.961	21.0
28	338.520	376.088	-37.569	29.3
29	315.020	331.689	-16.669	23.3
30	261.060	178.512	82.548	2.6
31	537.060	406.428	130.632	33.4
32	169.740	451.567	-281.827	39.5
33	645.540	494.486	151.053	45.3

TABLE 7

INPUT-OUTPUT DATA FOR MAJOR HIGHWAYS

County	Cost per Lane-Mile for Labor, Equipment, and Materials			Snow-fall (in.)	Average Daily Traffic
	Value	Estimate	Residual		
1	203.750	257.220	-53.470	38.5	3,732.0
2	171.880	160.161	11.719	29.0	2,120.0
3	198.860	182.767	16.093	29.5	2,698.0
4	225.050	103.468	121.581	11.0	2,651.0
5	173.820	212.478	-38.658	31.0	3,358.0
6	115.170	201.010	-85.840	42.7	1,651.0
7	289.990	268.876	21.114	48.6	2,866.0
8	260.500	238.540	21.960	35.9	3,513.0
9	195.420	234.933	-39.513	40.9	2,820.0
10	320.060	340.268	-20.209	43.3	5,505.0
11	399.960	199.931	200.029	22.7	3,986.0
12	197.610	210.582	-12.972	16.8	4,984.0
13	177.050	202.321	-25.271	32.9	2,847.0
14	277.020	186.519	90.501	33.7	2,307.0
15	231.960	249.320	-17.360	27.9	4,763.0
16	245.910	225.507	-20.403	38.4	2,850.0
17	248.790	281.357	-32.567	49.9	3,064.0
18	346.610	234.330	112.280	22.4	4,991.0
19	150.100	233.991	-83.891	33.7	3,645.0
20	271.070	333.438	-62.368	43.6	5,277.0
21	262.930	299.085	-36.156	44.3	4,226.0
22	249.640	330.023	-80.383	44.9	5,027.0
23	196.290	249.947	-53.657	38.5	3,527.0
24	455.500	347.024	108.476	63.3	3,330.0
25	221.330	220.347	0.983	18.4	5,070.0
26	363.300	220.009	143.291	16.4	5,297.0
27	324.520	262.376	62.144	22.7	5,746.0
28	393.510	532.478	-138.968	47.7	10,402.0
29	281.640	337.724	-56.084	49.5	4,700.0
30	162.680	223.819	-61.139	37.0	2,968.0
31	204.730	235.847	-31.117	20.8	5,223.0
32	147.390	229.357	-81.967	38.1	2,994.0
33	230.580	215.024	15.556	37.5	2,661.0
34	163.070	258.106	-95.036	31.0	4,644.0
35	164.520	247.597	-83.077	36.9	3,650.0
36	165.520	105.280	60.240	17.9	1,886.0
37	240.890	253.173	-12.283	36.9	3,819.0
38	186.900	223.723	-36.823	40.3	2,575.0
39	300.730	369.642	-68.912	28.9	8,036.0
40	232.470	202.280	30.190	27.2	3,520.0
41	191.660	243.168	-51.508	20.6	5,453.0
42	235.410	184.667	50.743	28.6	2,858.0
43	212.150	284.258	-72.108	45.4	3,678.0
44	150.710	117.140	33.570	16.6	2,374.0
45	331.080	172.762	158.317	31.8	2,144.0
46	217.830	276.277	-58.447	50.0	2,909.0
47	141.670	208.217	-66.547	21.8	4,326.0
48	170.150	177.497	-7.347	11.3	4,702.0
49	283.860	234.754	49.106	44.4	2,401.0
50	182.920	267.766	-84.846	29.1	5,141.0
51	176.590	368.637	-192.047	21.0	8,942.0
52	292.960	367.595	-74.635	29.3	7,931.0
53	129.340	155.934	-26.594	23.3	2,675.0
54	164.400	156.404	7.995	22.0	2,842.0
55	137.110	121.709	15.401	22.5	1,805.0
56	249.930	176.323	73.607	23.5	3,226.0
57	245.660	271.433	-25.773	20.8	6,226.0
58	275.160	282.856	-7.696	27.2	3,665.0
60	158.040	205.076	-47.036	36.0	2,558.0
61	140.050	145.196	-5.146	15.0	3,354.0
62	206.210	169.995	36.215	26.6	2,681.0
63	174.740	156.130	18.610	36.3	1,143.0
64	160.140	119.246	40.894	32.0	612.0
65	118.880	95.327	23.553	2.6	3,415.0
66	346.370	249.160	97.210	33.4	4,108.0
67	230.370	256.778	-26.408	35.3	4,098.0
68	226.880	189.858	37.022	37.1	1,999.0
69	379.530	382.289	-2.760	56.4	5,140.0
70	254.020	275.005	-20.985	39.5	4,115.0
71	993.790	652.513	341.277	45.3	14,069.0
72	629.640	510.691	118.949	102.1	3,354.0

TABLE 8

INPUT-OUTPUT DATA FOR AUXILIARY AND LOCAL HIGHWAYS

County	Cost per Lane-Mile for Labor, Equipment, and Materials			Snowfall (in.)	Average Daily Traffic
	Value	Estimate	Residual		
1	198.950	250.834	-51.884	38.5	2,078.0
2	101.760	183.522	-81.762	29.0	1,409.0
3	104.820	167.022	-62.202	29.5	1,046.0
4	155.090	90.038	65.052	11.0	818.0
5	127.030	156.781	-29.751	31.0	737.0
6	110.830	204.451	-93.621	42.7	861.0
7	85.200	210.998	-125.798	48.6	576.0
8	150.420	173.225	-22.805	35.9	719.0
9	296.390	229.888	66.502	40.9	1,493.0
10	271.860	235.366	36.494	43.3	1,433.0
11	234.160	179.535	54.625	22.7	1,773.0
12	121.930	122.203	-0.273	16.6	1,049.0
13	121.020	192.400	-71.380	32.9	1,311.0
14	240.210	190.551	49.659	33.7	1,218.0
15	200.890	193.419	7.471	27.9	1,683.0
16	195.320	189.125	6.196	38.4	859.0
17	231.150	228.034	3.116	49.9	823.0
18	264.030	185.771	78.258	22.4	1,918.0
19	116.620	179.529	-62.909	33.7	999.0
20	177.550	270.957	-93.407	43.6	2,119.0
21	207.220	239.562	-32.342	44.3	1,446.0
22	278.390	232.375	46.015	44.9	1,261.0
23	230.370	194.411	35.959	38.5	957.0
24	478.360	302.914	175.446	63.3	1,368.0
25	223.470	197.579	25.891	18.4	2,434.0
26	344.850	174.491	170.358	16.4	2,116.0
27	261.430	207.068	54.362	22.7	2,320.0
28	301.090	409.495	-108.405	47.7	4,583.0
29	319.450	278.712	40.738	49.5	1,858.0
30	203.040	171.433	31.607	37.0	606.0
31	167.840	150.913	16.927	20.8	1,338.0
32	126.030	173.214	-47.184	38.1	564.0
33	176.360	189.612	-13.252	37.5	932.0
34	134.230	182.199	-47.969	31.0	1,242.0
35	118.710	205.708	-86.998	36.9	1,294.0
36	171.040	116.786	54.254	17.9	864.0
37	156.770	189.147	-32.377	36.8	972.0
38	183.590	201.288	-17.698	40.3	967.0
39	191.760	231.488	-39.728	28.9	2,369.0
40	239.410	168.038	71.372	27.2	1,228.0
41	164.820	126.447	38.373	20.6	866.0
42	142.830	155.732	-12.902	28.6	885.0
43	206.030	269.680	-63.650	45.4	1,967.0
44	198.380	117.266	81.114	16.6	965.0
45	205.250	158.305	46.945	31.8	711.0
46	156.920	232.918	-75.998	50.0	913.0
47	171.200	176.184	-4.984	32.4	1,024.0
48	158.580	175.644	-17.064	21.8	1,759.0
49	146.260	132.977	13.287	11.3	1,650.0
50	122.040	210.874	-88.834	44.4	869.0
51	239.870	289.273	-49.403	29.1	3,503.0
52	251.980	456.386	-204.406	21.0	7,393.0
53	320.940	323.755	-2.815	29.3	4,174.0
54	133.330	181.056	-47.276	23.3	1,761.0
55	140.820	125.717	15.103	22.0	753.0
56	129.250	123.461	5.789	22.5	673.0
57	150.510	142.857	7.653	23.5	988.0
58	157.170	125.243	31.927	20.8	828.0
59	138.370	144.936	-6.566	27.2	769.0
60	161.270	164.484	-3.214	22.6	1,481.0
61	120.190	168.244	-48.054	36.0	613.0
62	69.130	85.780	-16.650	15.0	452.0
63	79.950	127.862	-47.912	26.6	472.0
64	93.410	158.686	-65.276	36.3	402.0
65	105.320	137.873	-32.553	32.0	291.0
66	109.910	56.016	53.894	2.6	733.0
67	193.860	174.993	18.867	33.4	930.0
68	206.630	197.979	8.651	35.3	1,253.0
69	206.680	180.696	25.984	37.1	783.0
70	257.460	267.207	-9.747	56.4	1,144.0
71	290.920	212.549	78.371	39.5	1,247.0
72	754.510	437.337	317.173	45.3	5,305.0
73	571.440	485.302	86.138	102.1	2,262.0

Generally speaking, greater reliability results from a greater number of observations. At the time this method was first used, data for only 2 years were available. As discussed later, models have now been produced from 3 years of data, and it is planned to use 4 years of data for producing models at the end of the present winter season when the weather data are available.

USE OF MODELS

By using data for the 2 years 1967 and 1968, the models projected the cost for snow and ice control in each county based on average 30-year snowfall and ADT values for each county. The resulting cost per lane-mile for each of the 5 types of routes was then applied to the mileage in each county to compute total funds to be allocated to the individual counties.

The money thus allocated to each county was then budgeted 18 percent for personnel, 19 percent for equipment, and 63 percent for material, as indicated by snow- and ice-control records of 1967 and 1968. By using other regression models for maintenance costs, exclusive of snow and ice control, similar allocations of funds were made to each county. These funds were budgeted 47 percent for personnel, 28 percent for equipment, and 25 percent for material. By combining the money for snow- and ice-control personnel and the money for other maintenance personnel allocated to each county, a labor quota was established. The determination of these quotas was one of the primary objectives of the work utilizing regression models.

TABLE 9

SNOW AND ICE CONTROL COSTS PER LANE-MILE ON INTERSTATE HIGHWAYS PREDICTED BY REGRESSION MODELS USING 30-YEAR MEAN ANNUAL SNOWFALL

County	Snowfall (in.)	Cost per Lane-Mile ($)
Warren	20	307
Wood	30	381
Medina	41	463
Summit	50	529
Cuyahoga	65	640
Ashtabula	75	714

Note: Costs are for plowing, spreading chemicals, and cleaning bridges.

TABLE 10

COMPARISON OF REGRESSION MODELS USING 2 AND 3 YEARS OF DATA

Highway	Years of Data	Model Equations	Multiple Correlation Factor
Interstate	2	$Y = 7.40 X_1 + 159.27$	0.44
	3	$Y = 9.49 X_1 + 107.08$	0.60
Major	2	$Y = 4.20 X_1 + 0.04 X_2 - 36.75$	0.76
	3	$Y = 4.87 X_1 + 0.03 X_2 - 33.19$	0.80
Auxiliary and local	2	$Y = 3.54 X_1 + 0.05 X_2 + 9.92$	0.73
	3	$Y = 4.28 X_1 + 0.04 X_2 + 4.13$	0.80

An additional application of the models is the calculation of cost per lane-mile by using the actual snowfall experienced in any given year and comparing the cost from the model with the actual cost. Table 9 gives lane-mile values of direct cost of snow and ice control for Interstate highways in several counties with increasing amounts of snowfall.

As previously stated, the regression models referred to up to this time were based on input data for the 2 years 1967 and 1968. When 1969 data became available, models were produced using 3-year data. As would be expected, the models based on more data had higher R-values, multiple correlation coefficients. Table 10 gives a comparison of the models using 2 and 3 years of data and the R-values for each model. The snowfall in inches, X_1, is a factor of greater influence in the 3-year models, and the average daily traffic, X_2, is of lesser influence in the 3-year than in the 2-year models. It is planned to use 4-year data with regression analyses to further improve the models. Updated traffic data will also be used. We anticipate that with the use of 4-year data higher multiple correlation coefficients will be obtained. The R-value when squared and multiplied by 100 gives a percentage figure that indicates how well a regression model explains the relationship among the variables, in this case, the relationship among the cost of snow and ice control, snowfall, and traffic volume.

Although not within the scope of this paper, we are using regression models to budget all maintenance funds to the 88 counties in Ohio. The models used relate cost per lane-mile to average daily traffic by each of five types of routes for work other than snow and ice control. These models include constant terms that represent the basic maintenance costs not associated with the variations in traffic. This is a new method for budgeting maintenance funds in Ohio, and we believe it will be of increasing benefit as time goes on.

We have also used regression models to identify factors affecting maintenance cost in specific areas as follows:

Dependent Variable (cost per lane-mile)	Independent Variables
Cost of applying chemicals	Snowfall, ADT
Concrete pavement and berm maintenance cost	Age of pavement, region of state, number of days 32 F or below, ADT
Rest area maintenance cost	ADT, parking spaces, number of toilet fixtures
Cost of litter pickup	ADT, region of state

The Bureau of Planning Survey in the Department of Highways is using regression analysis in connection with the 14 urban transportation studies under way in Ohio. For this work the California BIMED programs mentioned earlier are being used to obtain the relationship between trips and various land use and socioeconomic variables.

We have found in Ohio that multiple-regression models produced by readily available computer programs are useful in budgeting maintenance and operations funds. These models can also be useful in establishing acceptable cost values that can be used to measure work performance. In addition, the factors that significantly affect maintenance costs can be determined. Regression analysis often indicates that factors assumed to be of major importance in their effect on cost are of only minor importance. We plan to increase our use of regression analysis in its application to highway maintenance management in Ohio, and we recommend the use of this statistical method.

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Informal Discussion

Question

You stated that regression models based on data from the 2 years 1967 and 1968 were used to project the cost of snow and ice control for the 1969 winter. What were your expenditures for 1967 and 1968, and what was your predicted value for the 1969 winter?

Miller

The total direct expenditure for snow and ice control in 1967 was $8,350,703. In 1968 this expenditure was $8,676,351, and in 1969 it dropped to $6,195,871. Our projection for use in the 1969 budget was $8,428,795. These values indicate that the 2 winters, 1967 and 1968, were average in intensity, whereas the 1969 winter was less severe than the 30-year average. The 1969-70 winter was very severe, and expenditures exceeded the 30-year projection value by approximately 66 percent.

The projection using 30-year weather values allocates approximately 30 percent of our total direct expenditures for snow and ice control. We believe money should be budgeted for average winter conditions. The models developed with multiple regression provide a means for doing this and allocate the money for snow and ice control to each of 88 counties in accordance with long-term weather in the respective counties.

In addition to using the models for budgeting, we also measure county performance by inserting actual weather values in the models and comparing the results thus calculated with the money used in each county. For example, in the northeastern part of the state, one county used 110 percent of the money allocated to it for material to take care of ice and snow work. In a county just south of the first county, only 87 percent of the material money was used although it was also in the relatively high snowfall area. If it be assumed that the highways were open and safe to travel in both counties, the second county referred to was more efficient in its snow- and ice-control work than the first county.

Owen Sauerlender

Do you use division data or county data?

Miller

Data used are from each county having mileage of the route type being studied. Most of the 88 counties have some mileage of route types 20, 30, 40, and 50; and 49 counties have Interstate mileage.

Sauerlender

How do you combine county data?

Miller

We do not combine county input data for regression analysis. The result of applying the regression model is cost per lane-mile for each county. The projected costs thus obtained for each county within a division are summed to determine the projected cost for the division.

Sauerlender

The point I am making is that each county is a separate observation. You get 2 observations, but you do not take into account the time factor.

Miller

You are suggesting that perhaps we were limited in what we could spend for snow and ice control from year to year. We were not limited.

Sauerlender

It is the identical problem of combining cross-sectional data with time series.

Miller

We just averaged both the weather data and the cost data for those 2 years.

Sauerlender

It seems to me that, in this statistical approach, the longer the period you use, the higher your correlation coefficients should be, and that in any one year, for example 1970-71, the pattern of snowfall might be significantly different from the 30-year pattern and, therefore, your allocations might be affected. The amount might be quite different.

P. A. Schaerer

I have much the same question. How close to the 30-year mean annual snowfall were the snowfalls in the 2-year or 3-year period you used for the analysis?

Miller

To answer your question, I would have to refer to the inches of snowfall in each county for the 2-year period and the 30-year mean. I do not have that information, but I do not believe it is as important as the snowfall pattern within individual years. If in 2 different years the snowfall in a given county is the same, say 30 in., but in one year this amount fell in 30 different storms whereas in the other year it fell in 10 different storms, the required snow-removal effort could be quite different. Although I think it would be well to include the number of storms contributing to the total annual snowfall, we did not do this and I do not believe such data are available for 30-year values.

L. Gary Byrd

Did you use cost per centerline-mile or cost per lane-mile for each class of highway? On the Interstate, did you make any allowance for interchanges? Was interchange mileage a separate part of your mileage?

Miller

We used cost per lane-mile for each class of highway in our study of snow- and ice-removal costs. We did not separate lane-miles at interchanges but included the interchange lane-mileage with the regular Interstate lane-mileage. The cost per centerline-mile for Interstate highways given in Table 3 is 4 times the cost per lane-mile. This is an approximation. The cost per lane-mile is accurate. The true cost per centerline-mile is slightly higher than the value given in the table.

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